CATERPILLAR C7 & GEP 6.5L(T) FUEL SYSTEM DURABILITY USING 25% ATJ FUEL BLEND

INTERIM REPORT
TFLRF No. 474

by
Adam C. Brandt
Edwin A. Frame
Douglas M. Yost

U.S. Army TARDEC Fuels and Lubricants Research Facility
Southwest Research Institute® (SwRI®)
San Antonio, TX

for
Ms. Patsy Muzzell
U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. W56HZV-09-C-0100 (WD32)

February 2015

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14. ABSTRACT
The U.S. Army has a desire to reduce its dependence on traditional petroleum based fuels. This report covers investigation into the use of an ATJ blended fuel in the Caterpillar C7 and General Engine Products 6.5L(T) diesel engines. With the technical issues presented in this report related to the CAT C7 evaluation and the desert operating condition GEP 6.5L(T) evaluations, a full analysis of the compatibility of the 25% ATJ blend is not possible. In general, the pre-test data acquired with the C7 engine suggests that the engine is compatible with the ATJ blend in regards to engine performance. Fuel system durability was not able to be assessed. For the GEP 6.5L(T) engine, good compatibility was observed with the 25% ATJ at ambient temperatures. Engine power remained consistent across the 210hr durability testing, and pre and post test engine performance and fuel system calibration data showed minimal changes in condition.

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EXECUTIVE SUMMARY

The U.S. Army has a desire to reduce its dependence on traditional petroleum based fuels. This report covers investigation into the use of an ATJ blended fuel in the Caterpillar (CAT) C7 and General Engine Products (GEP) 6.5L(T) diesel engines. These engines are representative of high density vehicles fielded by the U.S. Army tactical wheeled fleet. Testing was conducted to determine impact on engine performance, combustion, fuel system durability, combustion related deposits, and raw exhaust gas emissions. Based on previous ATJ work conducted, the ATJ blending stock was limited to a maximum of 25% of the total fuel volume to maintain a desired minimum cetane number of 40 to ensure proper engine operation. All fuels were additized at the minimum effective treat rate of corrosion inhibitor/lubricity improver (CI/LI).

With the technical issues presented in this report related to the CAT C7 evaluation and the desert operating condition GEP 6.5L(T) evaluations, a full analysis of the compatibility of the 25% ATJ blend is not possible. In general, pre test powercurves and fuel mapping data from the CAT C7 engine suggests reasonable compatible with the 25% ATJ in respect to engine performance at both ambient and desert operating conditions. No unusual engine operating conditions were noted, and overall engine output achieved expected levels based on test fuel and temperature conditions. Unfortunately, a full durability test of the C7 engine was unable to be completed due to unrelated technical issues experienced with the engine being evaluated. These issues were successfully ruled non-fuel related. No post test powercurves or fuel maps were conducted.

For the GEP 6.5L(T) engine, overall testing showed good compatibility with the 25% ATJ fuel blend at ambient conditions. Pre and post test powercurves demonstrated minimal changes in power output across the 210hr test duration, and pre and post test fuel system calibration data suggests that the minimum treat rate of the 25% ATJ was providing adequate protection of the fuel wetted components at ambient temperatures. No data were able to be acquired with the GEP engine at desert operating temperatures due to fuel system durability issues.

FOREWORD/ACKNOWLEDGMENTS

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The authors would like to acknowledge the contribution of the TFLRF technical support staff and administrative and report-processing support.

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ACRONYMS AND ABBREVIATIONS

ATJ – alcohol to jet
BSFC – brake specific fuel consumption
CAT – Caterpillar
CI/LI – corrosion inhibitor, lubricity improver
CO – carbon monoxide
CO2 – carbon dioxide
CRC – Coordinating Research Council
DOC – desert operating conditions
FMTV – Family of Medium Tactical Vehicles
GEP – General Engine Products
HC – hydrocarbon
HEUI – hydraulically actuated, electronically controlled, unit injector
hp – horsepower
hr/hrs – hour/hours
JP8 – jet propulsion 8
L - liter
Ft-lb – pound feet torque
MATV – MRAP All Terrain Vehicle
MRAP – Mine Resistant Ambush Protected
NA – naturally aspirated
NOX – nitrogen oxides
O2 – oxygen
RPM – revolution per minute
SOW – scope of work
SwRI – Southwest Research Institute
T - turbo
TARDEC – Tank Automotive Research, Development, and Engineering Center
TFLRF – TARDEC Fuels and Lubricants Research Facility
TWV – tactical wheeled vehicle
TWVC – tactical wheeled vehicle cycle
ULSD – ultra low sulfur diesel
WOT – wide open throttle

1.0 BACKGROUND & INTRODUCTION

The U.S. Army has a desire to reduce its dependence on traditional petroleum based fuels. Extensive research has been conducted in past years to investigate various alternative fuel performance, and to qualify fuels for use in military ground equipment. Recent investigation has focused on the viability of alcohol to jet (ATJ) based fuels as a blending component with traditional petroleum based aviation fuels. This report covers investigation into the use of an ATJ blended fuel in the Caterpillar (CAT) C7 and General Engine Products (GEP) 6.5L(T) diesel engines. These engines are representative of high density vehicles fielded by the U.S. Army tactical wheeled fleet. All testing was conducted at the U.S. Army TARDEC Fuels and Lubricants Research Facility (TFLRF), located at Southwest Research Institute (SwRI), San Antonio TX.

2.0 OBJECTIVE

The objective of this testing was to determine the compatibility of ATJ blended fuels for use in high density military diesel engines utilized in the U.S. Army tactical wheeled vehicle (TWV) fleet. Testing was conducted to determine impact on engine performance, combustion, fuel system durability, combustion related deposits, and raw exhaust gas emissions. Based on previous ATJ work conducted, the ATJ blending stock was limited to a maximum of 25% of the total fuel volume to maintain a desired minimum cetane number of 40 to ensure proper engine operation [1,2,3]. All testing was conducted at the minimum effective treat rate of corrosion inhibitor/lubricity improver (CI/LI).

3.0 APPROACH

An engine dynamometer test stand was used to evaluate each engine while being operating on the ATJ fuel blend. Durability testing was preceded with full load powercurves to map engine maximum power and emissions as a function of engine speed (at max load). For the C7 engine, a fuel mapping test was also conducted to determine the brake specific fuel consumption (BSFC) of the engine across a wide range of engine speeds and loads. For the durability test, both engines

were run against an accelerated version of the 210hr Tactical Wheeled Vehicle Cycle (TWVC) outlined in CRC Report No. 406 [4], which was developed to determine fuel and lubricant compatibility with military engines. Modifications were made to the standard 210hr cycle to increase the daily operation time from 14hrs to 21hrs. This was accomplished by adjusting the rated speed step lengths, and reducing the daily engine off soak time. Table 1 shows the break-down of the adjusted step length durations.

Table 1. Accelerated 210hr Tactical Wheeled Vehicle Cycle

Cycle	Duration	Description
1	2hr 10min	Rated Speed & Load
	1hr	Idle
2	2hr 10min	Rated Speed & Load
	1hr	Idle
3	2hr 10min	Rated Speed & Load
	1hr	Idle
4	2hr 10min	Rated Speed & Load
	1hr	Idle
5	2hr 10min	Rated Speed & Load
	1hr	Idle
6	2hr 10min	Rated Speed & Load
	1hr	Idle
7	2hr	Rated Speed & Load
Soak	3hr	Engine Off

After the 210hr test was completed, post-test powercurves were conducted to determine end of test engine performance and emissions to define the overall ATJ blended fuels impact on engine operation.

4.0 FUEL PROPERTIES

Both engines were evaluated using identical 25% ATJ blends. The ATJ blend stock was provided by the U.S. Army TARDEC, and was mixed with commercially available Jet-A fuel sourced by TFLRF. The fuel blend was additized consistent to MIL-DTL-83133 NATO F-34 (JP8) fuel specifications. All additive concentrations blended into the fuel were sufficient for the total

blended volume (target concentrations: 9g/m^3 CI/LI, 1g/m^3 STADIS, 0.09% FSII). The fuel was blended in bulk batches on-site at TFLRF. Table 1, Table 2, Table 3, and Table 4 present the resulting fuel properties. Two separate batches were produced (AF-9186 batch 1 for the C7 work, and AF-9367 batch 2 for the GEP work).

Table 2. Chemical & Physical Properties of Evaluated 25% ATJ Blend

Test	ASTM Method	Units	SwRI Sample ID CL15-8613 Results	Min	Max
Saybolt Color	**D156**	--	22		
Acid Number	**D3242**	mg KOH / g	0.004		0.015
Chemical Composition	**D1319**				
Aromatics		vol %	13.3		25.0
Olefins		vol %	1.4		
Saturates		vol %	85.3		
Sulfur Content	**D4294**	mass %	0.074		0.30
Sulfur Mercaptan	**D3227**	mass %	0.0003		0.002
Doctor Test	**D4952**	--	Sweet		Negative
Distillation	**D86**				
IBP		°C	172.4		
5% Rcvd		°C	182.6		
10% Rcvd		°C	183.4		205
15% Rcvd		°C	187.1		
20% Rcvd		°C	188.5		
30% Rcvd		°C	192.4		
40% Rcvd		°C	196.1		
50% Rcvd		°C	200.3		
60% Rcvd		°C	205.8		
70% Rcvd		°C	212.2		
80% Rcvd		°C	221.6		
90% Rcvd		°C	233.9		
95% Rcvd		°C	243		
FBP		°C	256.3		300
Residue		%	1.0		1.5
Loss		%	0.7		1.5
T50-T10		°C	16.9		
T90-T10		°C	50.5		

Table 3. Chemical & Physical Properties of Evaluated 25% ATJ Blend

Test	ASTM Method	Units	SwRI Sample ID CL15-8613 Results	Min	Max
Flash Point	**D93**	°C	56.5	38	
Density	**D4052**				
Test Temperature		°C	15		
Density		kg/m³	786.9	775.0	0.840
Freeze Point (Manual)	**D2386**	°C	-52		-47
Kinematic Viscosity	**D445**				
Test Temperature		°C	40		
Viscosity		mm²/s	1.35		
Net Heat of Combustion	**D4809**	MJ/kg	43.4	42.8	
Hydrogen Content (NMR)	**D3701**	mass %	14.44	13.4	
Smoke Point	**D1322**	mm	26.8	25	
Naphthalene Content	**D1840**	vol %	0.64		
Calculated Cetane Index	**D976**	--	50.0		
Copper Strip Corrosion	**D130**				
Test Temperature		°C	100		
Test Duration		hrs	2		
Rating		--	1A		No. 1
JFTOT	**D3241**				
Test Temperature		°C	260		
ASTM Code		rating	1		
Maximum Pressure Drop		mmHg	0		25
Ellipsometer		nm	6.85		<3^9
Total Volume		cm^3	9.60E-07		
Gum Content	**D381**	mg / 100 mL	2		7.0
MSEP	**D7224**	-	81		
Particulate Matter	**D5452**				
Total Contamination		mg/L	0.7		1.0
Total Volume Used		mL	1000		
Water Reaction	**D1094**				
Volume Change of Aqueous Layer		mL	1		
Interface Condition		rating	1B		1B
Separation		--	2		
BOCLE	**D5001**	mm	0.54		0.65

Table 4. Chemical & Physical Properties of Evaluated 25% ATJ Blend

Test	ASTM Method	Units	SwRI Sample ID CL15-8613 Results	Min	Max
Fuel System Icing Inhibitor (FSII) Content	**D5006**				
Test Temperature		°C	20.5		
FSII Content		vol %	0.10	0.07	0.10
Electrical Conductivity	**D2624**				
Electrical Conductivity		pS/m	172		
Temperature		°C	20.5		
Hydrocarbon Types by Mass Spec.	**D2425**				
Paraffins		mass %	60.0		
Monocycloparaffins		mass %	24.9		
Dicycloparaffins		mass %	0.0		
Tricycloparaffins		mass %	0.0		
Total Naphthalenes		mass %	24.9		
TOTAL SATURATES		mass %	84.9		
Alkylbenzenes		mass %	9.8		
Indans/Tetralins		mass %	3.7		
Indenes		mass %	0.2		
Naphthalenes		mass %	0.3		
Alkyl Naphthalenes		mass %	0.8		
Acenaphthenes		mass %	0.1		
Acenaphthylenes		mass %	0.1		
Tricycl- Aromatics		mass %	0.0		
Total PNAs		mass %	1.3		
TOTAL AROMATICS		mass %	15.0		
Carbon Hydrogen	**D5291 CH**				
Carbon		mass %	85.41		
Hydrogen		mass %	14.46		
Total		mass %	100.01	99.5	
Nitrogen Content	**D4629**	ppm	<1.0		2
Karl Fisher Water Content	**D6304**	mg/kg	53		75
Total F, CL, S by Combustion Ion Chromotography	**D7359**				
F		ppm	0.04		1
Cl		ppm	0.44		1
S		ppm	3.0		1
Kinematic Viscosity	**D445**				
Test Temperature		°C	-20		
Viscosity		mm²/s	4.558		8.0

Table 5. Chemical & Physical Properties of Evaluated 25% ATJ Blend

Test	ASTM Method	Units	SwRI Sample ID CL15-8613 Results	Min	Max
Particle Count by APC (Cumulative)	**ISO4406**				
>= 4um		code	23		
>= 6um		code	21		
>= 14um		code	15		
>= 21um		code	12		
>= 38um		code	0		
>= 70um		code	0		
Elements	**UOP389**				
Al		mg/kg	<0.02		0.1
Ca		mg/kg	0.03		0.1
Co		mg/kg	<0.02		0.1
Cr		mg/kg	<0.02		0.1
Cu		mg/kg	0.04		0.1
Fe		mg/kg	0.05		0.1
K		mg/kg	<0.02		0.1
Li		mg/kg	<0.02		0.1
Mg		mg/kg	<0.02		0.1
Mn		mg/kg	<0.02		0.1
Mo		mg/kg	<0.02		0.1
Na		mg/kg	0.11		0.1
Ni		mg/kg	<0.02		0.1
P		mg/kg	<0.02		0.1
Pb		mg/kg	<0.02		0.1
Sn		mg/kg	<0.02		0.1
Sr		mg/kg	<0.02		0.1
Ti		mg/kg	<0.02		0.1
V		mg/kg	<0.02		0.1
Zn		mg/kg	<0.02		0.1
Pt		mg/kg	<0.02		0.1
Pd		mg/kg	<0.02		0.1

In addition to the 25% ATJ fuel blend, commercially available ultra low sulfur diesel (ULSD) was utilized in the pre-test power curves for both the C7 and GEP engines to establish pre-test engine performance. Table 5, Table 6 and Table 7 present the chemical and physical properties of the tested ULSD.

Table 6. Chemical & Physical Properties of Evaluated ULSD

Test	ASTM Method	Units	SwRI Sample ID CL15-8794 Results
Flash Point	**D93**	°C	60
Water and Sediment	**D2709**		
Sample Description		--	--
Total Contaminant		vol %	<0.005
Distillation	**D86**		
IBP		°C	172.4
5% Rcvd		°C	198.2
10% Rcvd		°C	200.5
15% Rcvd		°C	217.8
20% Rcvd		°C	226.6
30% Rcvd		°C	243.3
40% Rcvd		°C	258.3
50% Rcvd		°C	271.3
60% Rcvd		°C	283.0
70% Rcvd		°C	294.4
80% Rcvd		°C	307.1
90% Rcvd		°C	324.6
95% Rcvd		°C	340.8
FBP		°C	345.1
Residue		%	1.3
Loss		%	1.3
T50-T10		°C	70.8
T90-T10		°C	124.1
Kinematic Viscosity	**D445**		
Test Temperature		°C	40
Viscosity		mm^2/s	2.67
Kinematic Viscosity	**D445**		
Test Temperature		°C	80
Viscosity		mm^2/s	1.42
Kinematic Viscosity	**D445**		
Test Temperature		°C	-20
Viscosity		mm^2/s	Sample Frozen
Ash Content	**D482**	mass %	<0.001
Total Sulfur Content	**D5453**	mg/kg	8.9
Copper Strip Corrosion	**D130**		
Test Temperature		°C	50
Test Duration		hrs	3
Rating		--	1A
Cetane Number	**D613**	--	53
Calculated Cetane Index	**D976**	--	55.4

Table 7. Chemical & Physical Properties of Evaluated ULSD Cont.

Test	ASTM Method	Units	SwRI Sample ID CL15-8794 Results
Chemical Composition	**D1319**		
Aromatics		vol %	20.6
Olefins		vol %	2.0
Saturates		vol %	77.4
Cloud Point (Manual)	**D2500**	°C	-12
Cloud Point (Automated)	**D5773**	°C	-11.1
Cold Filter Plugging Point (CFPP)	**D6371**	°C	-11
Carbon Residue (10% Bottoms)	**D524**	wt%	0.06
Lubricity (HFRR)	**D6079**		
Test Temperature		°C	60
Wear Scar Diameter		um	473
Electrical Conductivity	**D2624**		
Electrical Conductivity		pS/m	89
Temperature		°C	22.2
Density (15°C)	**D4052**	kg/m³	828.8
Lubricity (BOCLE)	**D5001**	mm	0.482
Net Heat of Combustion	**D4809 NET**	MJ/kg	42.791
Derived Cetane Number (IQT)	**D6890**		
Ignition Delay		sec	3.892
Derived Cetane		--	52.41
Carbon Hydrogen	**D5291**		
Carbon		mass%	86.11
Hydrogen		mass%	13.68
Bulk Modulus	**BlkMod**		
29.9°C, 0 psi		psi	209,616
29.9°C, 100 psi		psi	210,144
29.9°C, 500 psi		psi	217,551
34.7°C, 0 psi		psi	202,557
34.7°C, 100 psi		psi	205,456
34.7°C, 500 psi		psi	208,276
64.8°C, 0 psi		psi	167,935
64.8°C, 100 psi		psi	169,062
64.8°C, 500 psi		psi	174,896
80.1°C, 0 psi		psi	150,901
80.1°C, 100 psi		psi	151,751
80.1°C, 500 psi		psi	158,109

5.0 ENGINE DESCRIPTION

The following sections present descriptions of each engine tested, including general description, identification of wheeled vehicle applications, and engine and fuel system specific serial numbers for tested hardware.

5.1 CATERPILLAR C7

The CAT C7 engine is a 7.2L turbo-charged, aftercooled, direct-injected, inline 6 cylinder engine, which produces approximately 330bhp at a rated speed of 2400rpm using diesel fuel. The C7 engine utilizes a hydraulically actuated electronically controlled unit injection (HEUI) fuel system. This engine is fielded in the Family of Medium Tactical Vehicles (FMTV), MRAP-All Terrain Vehicles (MATV), and the Stryker family of vehicles. The engine used in the C7 evaluation was SN: FM25123. A total of two injector sets were used, and are outlined below by serial number (identified by installed cylinder location):

Table 8. Caterpillar C7, Evaluated Injector Serial Numbers

CYL	SET 1	SET 2
1	3B12236088A2	3B136889464E
2	3B1222852462	3B13688893D7
3	3B1225588985	3B13688456CA
4	3B122558766B	3B136889656D
5	3B1225616577	3B13688579A6
6	3B1225611007	3B13688521DF

5.2 GENERAL ENGINE PRODUCTS 6.5L(T)

The GEP 6.5L(T) engine is a 6.5L turbo-charged, indirect-injected, V8 engine, which produces approximately 190bhp at a rated speed of 3200 rpm using diesel fuel. The GEP 6.5L(T) engine utilizes a fuel lubricated Stanadyne rotary-distributor fuel injection system in a pump line nozzle configuration. This family of engines includes the GEP 6.2L NA, 6.5L NA, and 6.5L(T) diesel engines, utilized in all variants of the High Mobility Multipurpose Wheeled Vehicle (HMMWV). The engine used in the GEP 6.5L(T) evaluation was SN: 0HTS-0515, and Stanadyne injection pump DB2-6282 SN: 17139503.

6.0 ENGINE INSTALLATION & TEST CELL

Each engine was fully instrumented to measure all pertinent temperatures, pressures and other relevant analog data. Both engines were installed and tested in TFLRF Test Cell 08. The following outlines the general setup of the engine and test cell installation:

- SwRI developed PRISM system was used for data acquisition and control.
- The following controllers were designed into the installation to meet required operating conditions called out in the SOW:
    - Engine speed
    - Throttle output
    - Coolant out temperature
    - Fuel inlet temperature
    - Air inlet temperature
    - Manifold air temperature (CAT C7 only)
- The engine was coupled with a driveshaft and torsional vibration coupling to a Midwest model 1519 (eddy current) 500hp wet gap dynamometer.
- Engine speed was controlled through dynamometer actuation, and engine load was controlled through engine throttle operation.
- Coolant temperature was controlled using laboratory process water and a shell and tube heat exchanger. A three way process valve was used to allow coolant to bypass the heat exchanger as required to manipulate engine temperature to desired levels.
- Inlet air was drawn in at ambient conditions into through two radiator type cores plumbed prior to the engines turbocharger inlet. The radiator cores were fitted with three way process control valves and used segregated sources of hot engine coolant and chilled laboratory water to control the temperature of the incoming air charge.

- Final intake manifold temperature (CAT C7 only) was controlled through the use of an air to water intercooler and a process control valve which allowed manipulation of water supply to the intercooler core.
- For the CAT C7 engine, the oil sump temperature was not controlled, and was ultimately regulated through the engine internal oil to water cooling system. Resulting oil temperature was purely a function of coolant temperature and general engine operating conditions (i.e., speed and load). For the GEP 6.5L(T) engine, the oil sump temperature was controlled through use of a plate style heat exchanger and laboratory process water.
- Fuel was supplied to the engine using a recirculation tank (or “day tank”) at ambient temperature and pressure conditions. The recirculation tank was connected to the engines fuel supply and return, and kept at a constant volume controlled through a float mechanism which metered the bulk fuel supply from the test cell to replenish the tank volume. This make-up fuel flow rate was measured by a Micromotion coriolis type flowmeter to determine the engine fuel consumption.
- Fuel temperature was controlled by routing fuel leaving the recirculation tank through a liquid to liquid heat exchanger that supplied required heat transfer (in either direction) to the incoming fuel from a temperature controlled secondary process fluid. This secondary process fluid (ethylene-glycol and water mix) was heated and cooled as needed by an inline circulation heater, a liquid to liquid heat exchanger coupled to the hot engine coolant, and liquid to liquid trim heat exchanger connected to the laboratory chilled water supply.
- The engine exhaust was routed to the building’s roof top exhaust handling system and discharged outside to the atmosphere. A butterfly valve was used to regulate engine exhaust backpressure as required during testing.
- Emissions were directly sampled from an exhaust probe installed between the engine and exhaust system backpressure valve. Raw emissions concentrations were measured using a Horiba MEXA-1600D Motor Exhaust Gas Analyzer, equipped with its own heated sample line and sample conditioning unit.
- Exhaust smoke was measured by an AVL Smoke Meter Model 4155E.

- Crankcase blow-by gasses were ducted into a containment drum to capture any entrained oil, and then routed to the atmosphere through a vortex shedding flow meter to measure flow rate.
- The engine was lubricated with MIL-PRF-2104H SAE 15W40 engine oil.
- Used oil samples were collected from the engine daily to monitor engine and oil condition.

7.0 RESULTS & DISCUSSION

The following sections discuss the results from each of the engine tests conducted using the ATJ blended fuel. Per the contract scope of work (SOW), pre and post test powercurves and the 210hr test duration operating conditions were specified as either ambient or desert-like operating conditions (DOC). A summary of specified testing based on each engine type is listed below:

- Caterpillar C7
    - Pre test powercurves with ULSD at both ambient and DOC
    - Pre and post test powercurves with 25% ATJ at both ambient and DOC
    - Pre and post test fuel maps with 25% ATJ at both ambient and DOC
    - 210hr test duration operated on 25% ATJ at DOC
- General Engine Products 6.5L(T)
    - Pre test powercurves with ULSD at both ambient and DOC
    - Pre and post test powercurves with 25% ATJ at both ambient and DOC
    - 210hr test duration operated on 25% ATJ at ambient

Table 9 identifies each of the temperature specifications based on type of operation specified.

Table 9. Engine Operation Conditions per SOW

Temperature Parameter	Ambient Conditions	Desert-Like Operating Conditions (DOC)
Inlet Air	77° +/- 4° F	120° +/- 4° F
Fuel Inlet	86° +/- 4° F	175° +/- 4° F
Engine Coolant	205° +/- 4° F	218° +/- 4° F (CAT C7) 205° +/- 4° F (GEP)
Intake Manifold	127° +/- 2° F	Range Proportional from 118° +/- 3° F (Idle) to 155° +/- 3° F (Full Load) (CAT C7)

7.1 CATERPILLAR C7

The following sections outline all testing conducted on the C7 engine. This includes pre-test powercurves at ambient and DOC, pre-test fuel maps at ambient and DOC, and discussion of results regarding the attempted 210hr test duration.

7.1.1 Summary

The CAT C7 ATJ test was attempted and was ultimately deemed inconclusive. All pre-test engine preparations and data acquisition was successfully completed, but upon initiation of the 210hr test duration, the engine began to experience unexpected power loss with every day of operation. At 126hrs testing was halted and a tele-conference was conducted with TARDEC to discuss the observed power degradation. From discussions, a theory was established regarding the minimum CI/LI treat rate of the 25% ATJ fuel blend causing advanced fuel system degradation resulting in the reduced power. This theory was based on acquired data showing a steady decrease in engine fuel consumption, corresponding drop in engine output power, and no evident causes noted when all other engine data was reviewed (manifold pressures, charge air temps, etc), and no active fault codes found in the engines electronic control unit (ECU).

Based on the proposed theory, replacement injectors were sourced to restore engine performance, and the fuel blend CI/LI was to be adjusted to the max allowable treat rate for the remainder of testing. Due to funding and contractual limitations, arrival of replacement injectors was delayed for approximately two months. During this time the engine remained down and off test.

Once the replacement injectors were received, a quick test was run to access current engine condition PRIOR to changing the original installed injectors. Unexpectedly it was observed that the engine power output returned and produced near start of test performance with no changes to the stand. Continued testing showed that with additional operation, the engine power output began to again decrease following approximately the same degradation rate as experienced previously. A second conference tele-conference was scheduled with TARDEC and the issue was further discussed.

As a result of the second teleconference, the replacement injectors were installed into the engine, and then the engine was operated for 20hrs under test conditions using ULSD. During this 20hrs of operation, the engine output power again degraded with time, demonstrating that the 25% blend was NOT the original cause of the engine power loss. Its most likely that this degradation was caused by some sort of engine controller or sensor issue that existed on the engine being evaluated. Some investigation was conducted into the engine controller/harness/sensors, but ultimately it was determined that the time and cost to fully investigate and correct the problem was outside of the scope of the project timeline and funding.

As a result, testing was officially stopped at 126hrs and all additional testing terminated. No post test data acquisition was completed due to the undiagnosed engine condition. Pre-test engine powercurve and fuel map data is reported in the following sections.

7.1.2 Pre-Test Powercurve

Figure 1, Figure 2, and Figure 3 show the CAT C7 pre-test powercurve data for engine power, torque, and break specific fuel consumption respectively. As shown, both the ULSD and 25% ATJ experience a marked reduction in output power and torque between ambient and DOC. Also noted is the near identical response between the 25% ATJ at ambient conditions versus the ULSD at DOC.

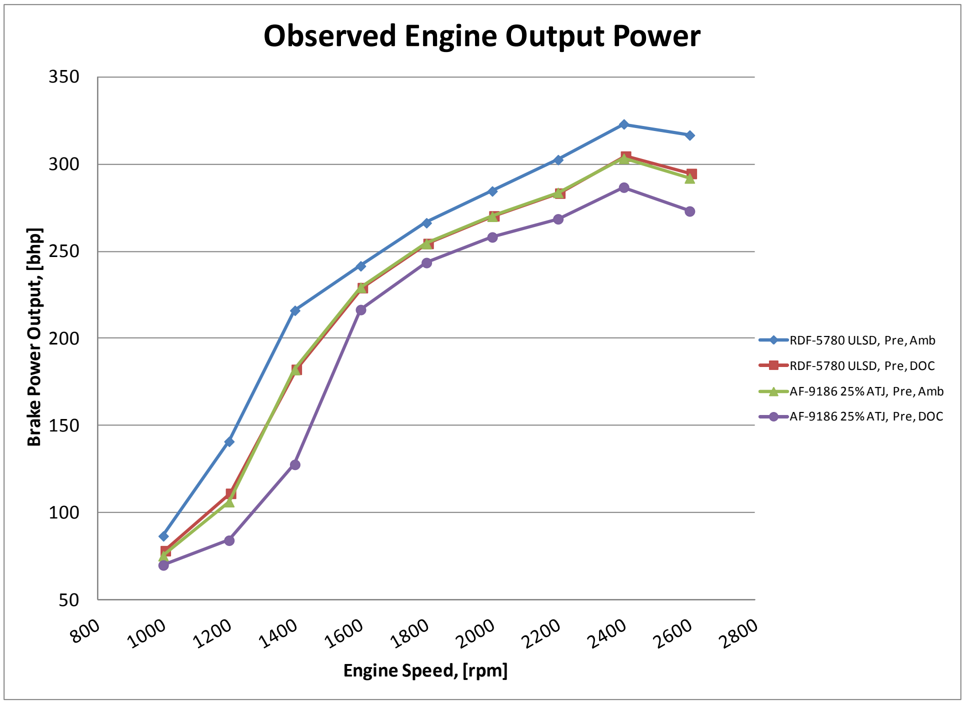

Figure 1. CAT C7 Powercurves – Engine Output Power

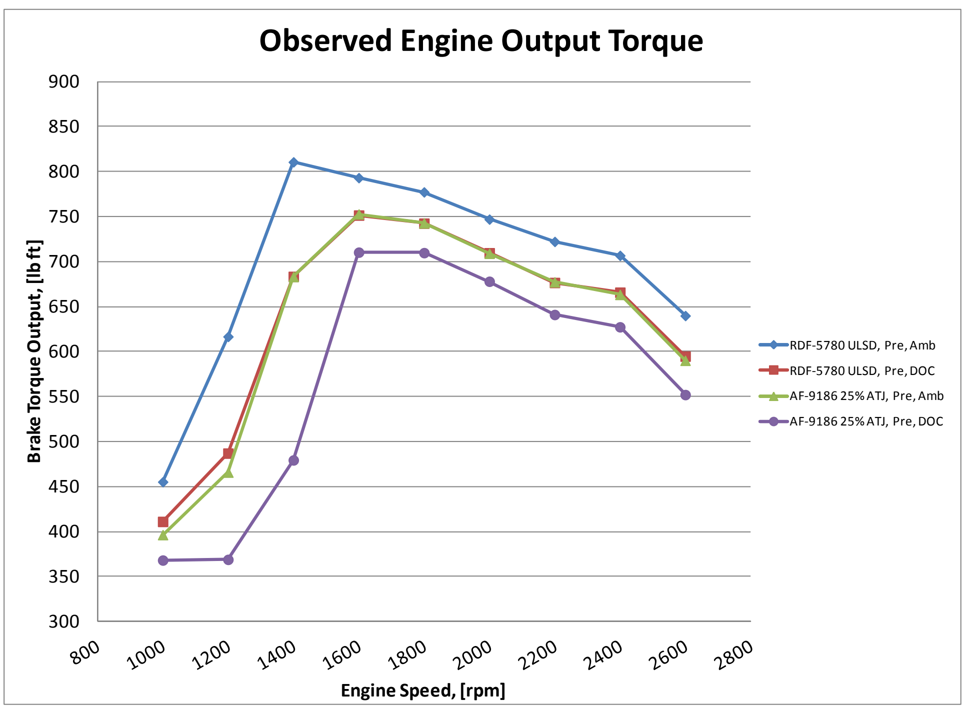

Figure 2. CAT C7 Powercurves – Engine Output Torque

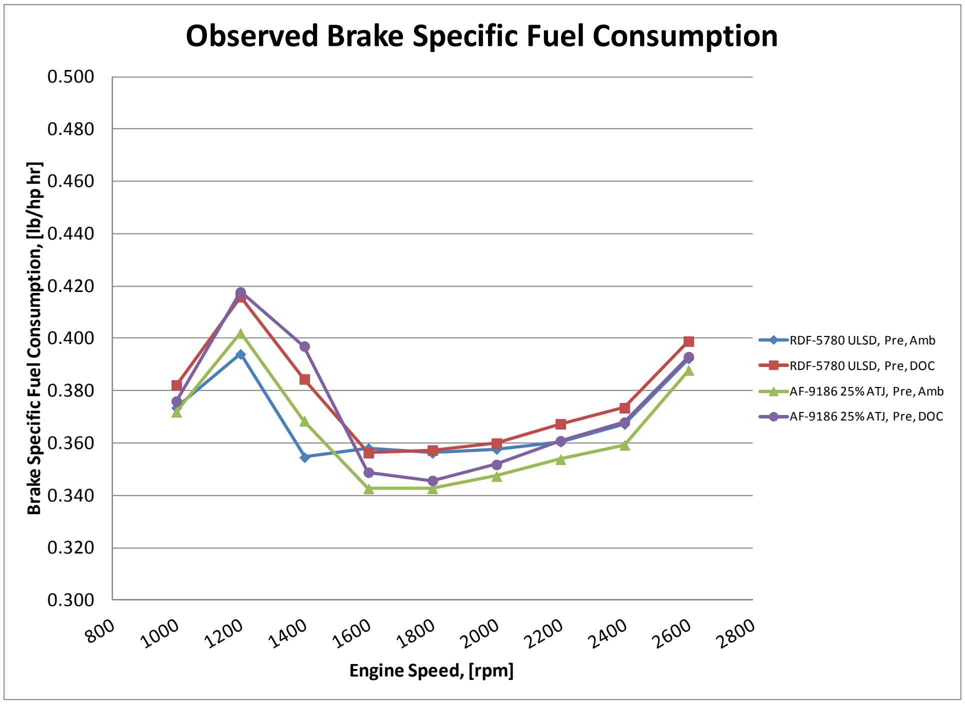

Figure 3. CAT C7 Powercurves – BSFC

7.1.3 Pre-Test Fuel Maps

Figure 4 and Figure 5 show the CAT C7 pre-test fuel maps for the 25% ATJ fuel at both ambient and DOC respectively. What is immediately noticeable is the pronounced hook along the 100% load line at the lower engine speeds, showing low engine speed output loss as operating temperature increased. The max efficiency island in the mid speed high load portion of the map also shrinks to a smaller area as temperature moves from ambient to DOC. This is generally expected with all engines as engine power suffers due to reduced air density. As well, the interior sections of the low speed portions of the map shift to a higher BSFC with increased temperature (Note, 10% and 20% load points for the 2200 and 2400 rpm speeds were unable to be hit due to parasitic water load applied by the dynamometer).

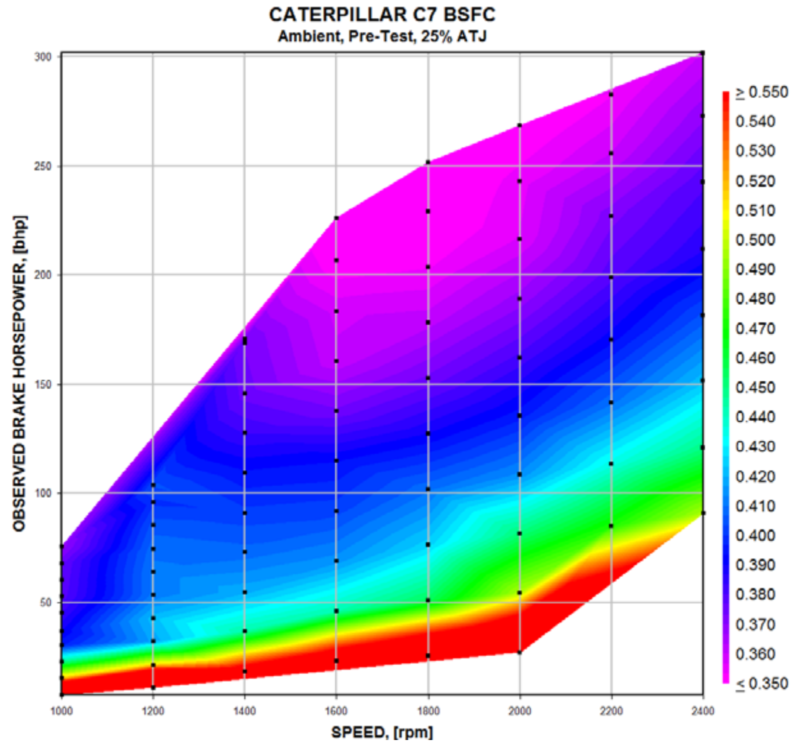

Figure 4. CAT C7 Pre Test Fuel Map 25% ATJ, Ambient Conditions

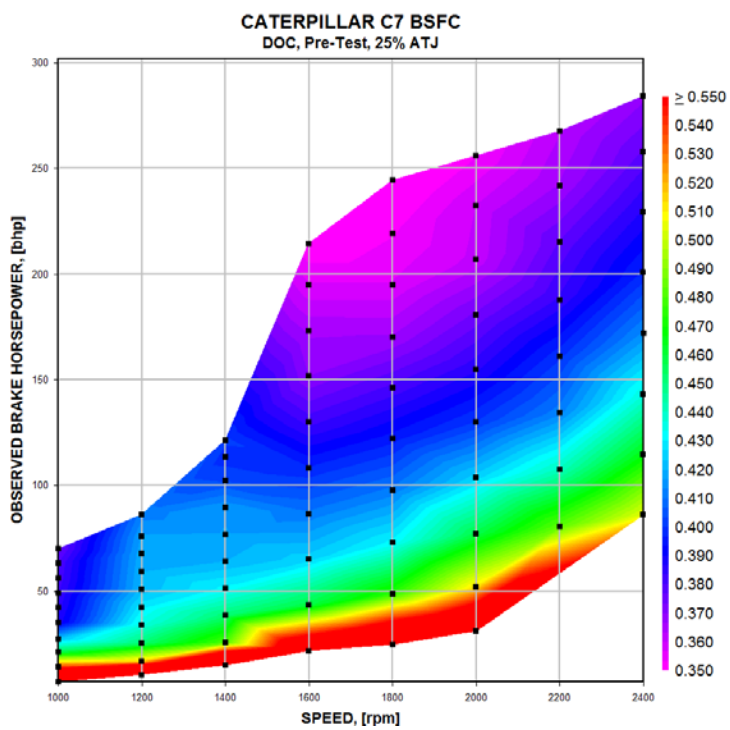

Figure 5. CAT C7 Pre Test Fuel Map 25% ATJ, Desert Operation Conditions

7.2 GENERAL ENGINE PRODUCTS 6.5L(T)

The following sections outline all testing conducted on the GEP 6.5L(T) engine. This includes pre-test powercurves at ambient and DOC, discussion of selected combustion pressure and heat release data, discussion the 210hr test duration results, pre and post test fuel system calibration information, and pre and post test photo documentation of the injectors and internal fuel wetted engine components.

7.2.1 Summary

The GEP engine completed all testing satisfactorily, with the exception of DOC powercurves for both the ULSD and 25% ATJ. DOC powercurves were dropped from the test matrix after the original injection pump failed during test stand shakedown work at DOC using ULSD. Some investigation was conducted into the cause of the injection pump failure (which was noted by low engine power output, and wear metal accumulation under the top cover of the injection pump). The failure was unexpected as other pump stand work using Stanadyne rotary pumps has been conducted at similar fuel inlet temperatures without causing immediate pump failure. The cause of the failure on the engine dyno stand was not readily identified. Ultimately it was determined that an in-depth investigation into the failure was outside of the project timeline and budget, and that DOC 25% ATJ powercurve data had already been generated under a previous fuel map generation work directive [5]. As a result the DOC requirement was dropped for GEP engine under this project. The remaining sections cover in greater detail the pre and post test powercurves, combustion analysis, 210hr operating summary, fuel system data, and pre and post test photographs.

7.2.2 Pre & Post Test Powercurves & Emissions

Figure 6, Figure 7, and Figure 8 show the GEP 6.5L(T) powercurve data for power, torque, and BSFC respectively. As expected, some reduction in power is noted between the ULSD and 25% ATJ curves. This is attributed to the lower viscosity, and lower density of the 25% ATJ blended fuel.

Across the 210hr test duration for the 25% ATJ blend, engine output power did not significantly change. Some increase in engine torque (and corresponding power) was noted around the peak torque speed of the engine, but was minor overall. BSFC did show an increase between the start

and end of testing at the higher engine speeds, suggesting that the overall efficiency of the engine had decreased across the 210hr duration. Increased fueling rate can be attributed to internal wear of the injection pump at the shoe, roller, and plunger interfaces, effectively increasing the stroke of the plunger and increasing fuel delivery. Despite this, overall powercurve data suggests that the minimum treat rate of CI/LI in the 25% ATJ blend was providing adequate protection of the fuel system when operated at ambient conditions.

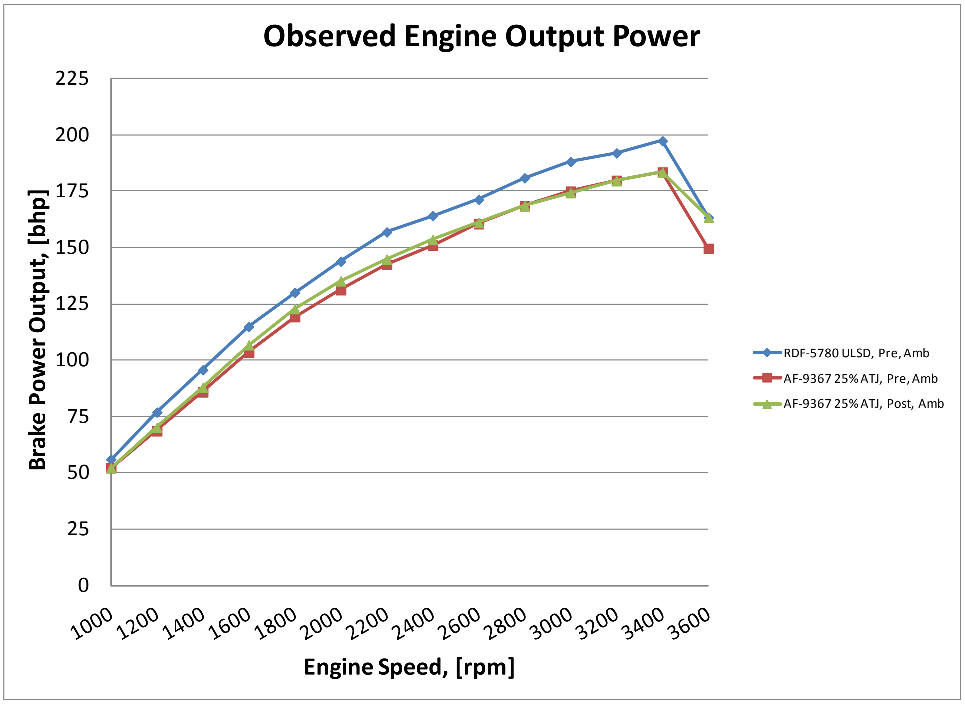

Figure 6. GEP 6.5L(T) Powercurves – Engine Output Power

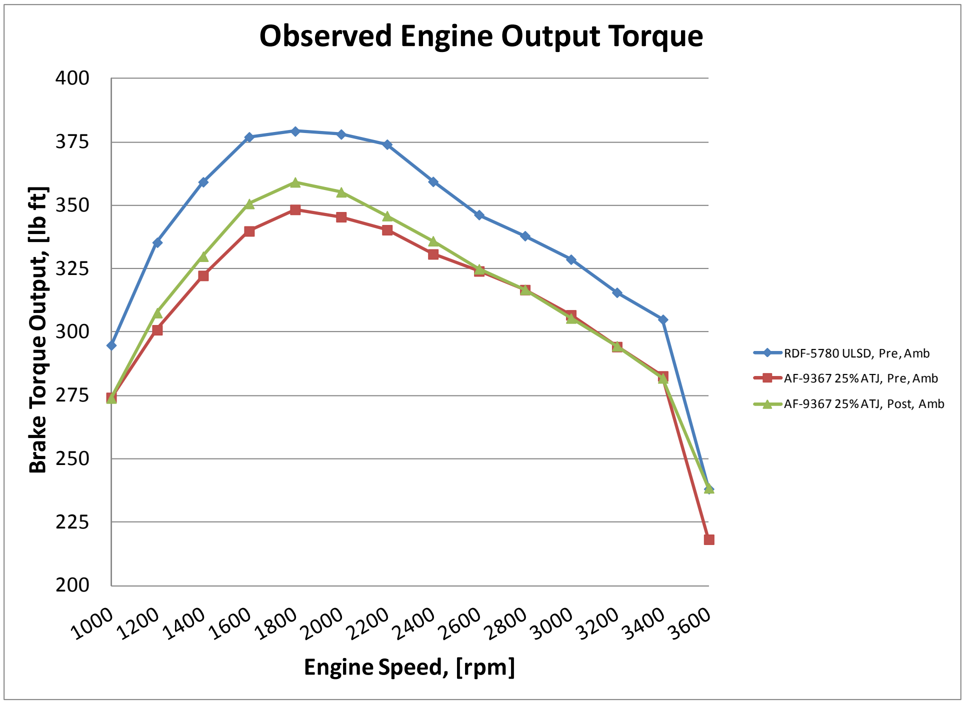

Figure 7. GEP 6.5L(T) Powercurves – Engine Output Torque

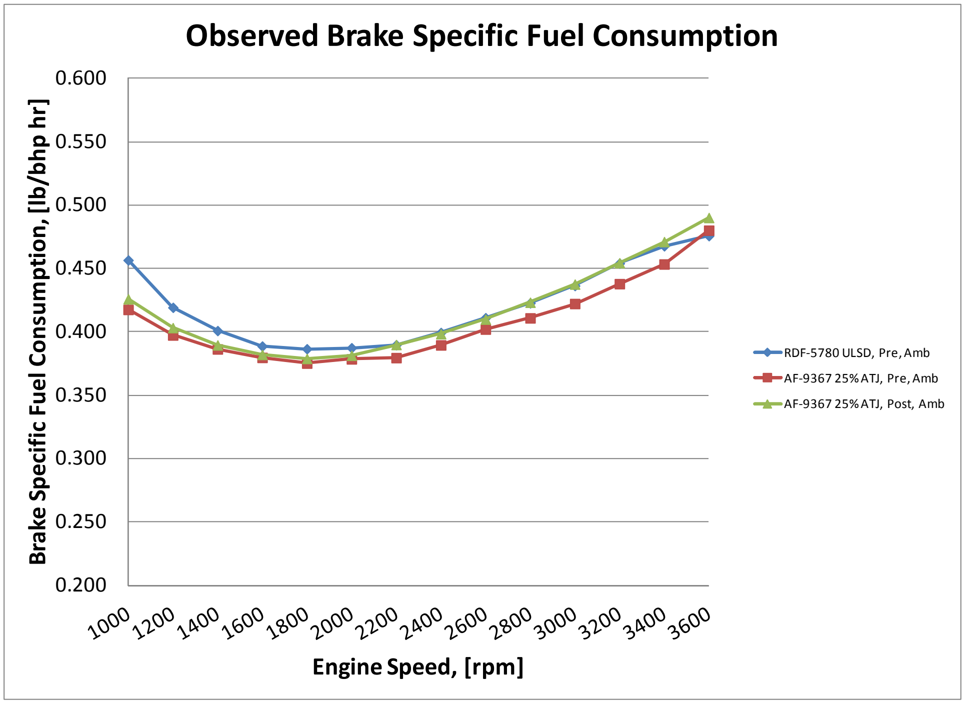

Figure 8. GEP 6.5L(T) Powercurves – BSFC

Figure 9 through Figure 14 show the raw exhaust emission concentrations for the pre test ULSD and 25% ATJ, and post test 25% ATJ powercurves for the GEP 6.5L(T) engine. For the more critical emissions (CO, NOX, and HC), only minor changes were noticed between the pre test ULSD and 25% ATJ curves. For CO, the 25% ATJ shows a consistent reduction compared to the ULSD. The opposite is seen with NOX, where the 25% ATJ at pre test conditions was slightly increased. Directionally this tends to make sense, as NOX is typically a result of higher combustion temperatures, and the oxidation of CO to CO2 is also effected by gas temperatures. For pre test HC, both the ULSD and 25% ATJ blend response was very low, and difference between their reported magnitude are insignificant based on the measurement calibration range and repeatability of the emissions measurement equipment.

For the 25% ATJ pre and post test comparison, CO response does not change significantly across the test duration. NOX concentrations did show a decrease which suggests a lower overall bulk combustion temperature than during pre test powercurves. Again for HC the measured response is fairly low, with the exception of a pronounced spike at the higher engine speeds (3000 rpm and beyond). The exact cause of this spike is unknown, but is likely related to the higher oil consumption that was noted in the GEP engine towards the end of testing. (NOTE: 1000 and 1200 rpm post test measurements were unable to be included due to a fault in the exhaust sample handling system at the time of testing. The issue was resolved prior to the 1400 rpm and remaining speed/load points).

Exhaust smoke measurements showed a consistent decrease between the ULSD and both pre and post test 25% ATJ blend testing. This is expected based on the composition of the JP8 and synthetic ATJ portion of the fuel compared to ULSD. Both fuels generated smoke numbers of approximately 3 or below at engine speeds above peak torque. Below peak torque, as the engine air flow reduces, both fuels generated much higher smoke numbers.

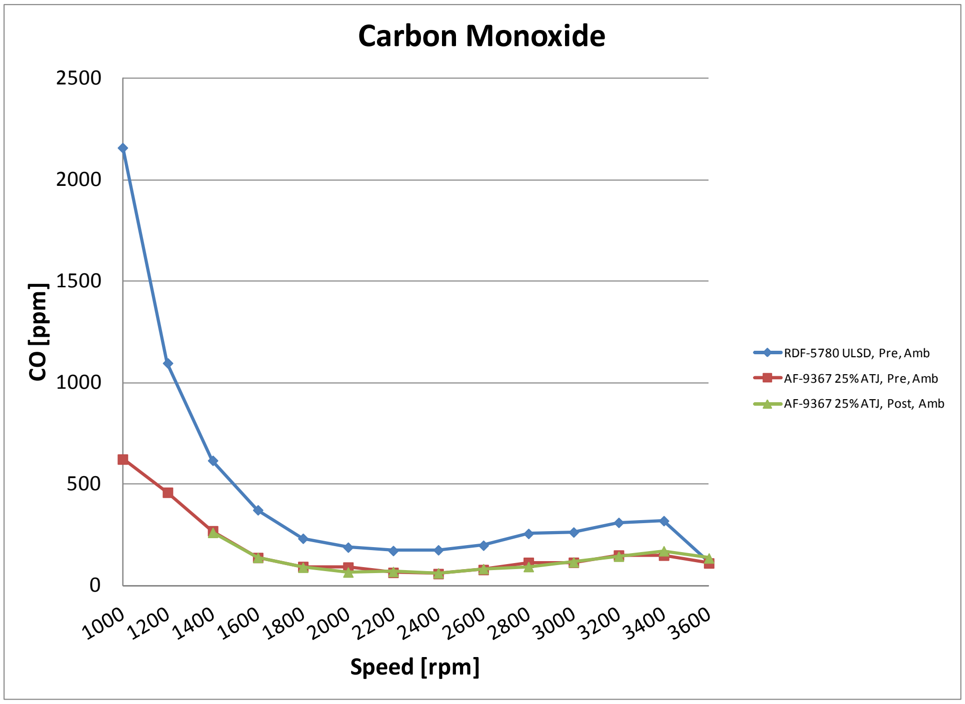

Figure 9. GEP 6.5L(T) Raw Emissions - CO

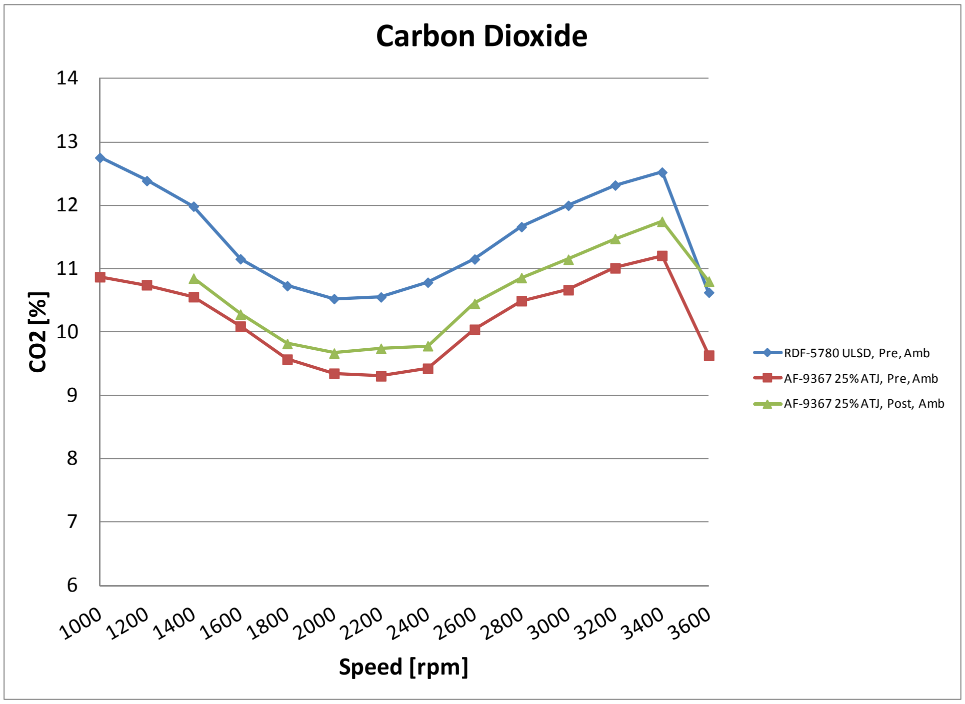

Figure 10. GEP 6.5L(T) Raw Emissions – CO2

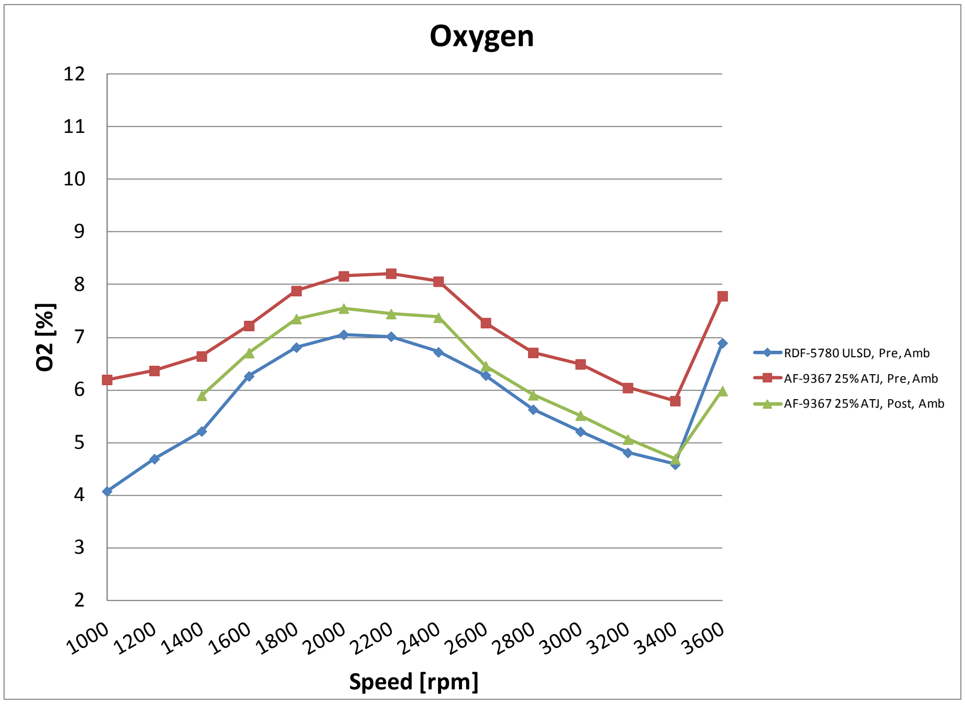

Figure 11. GEP 6.5L(T) Raw Emissions – O2

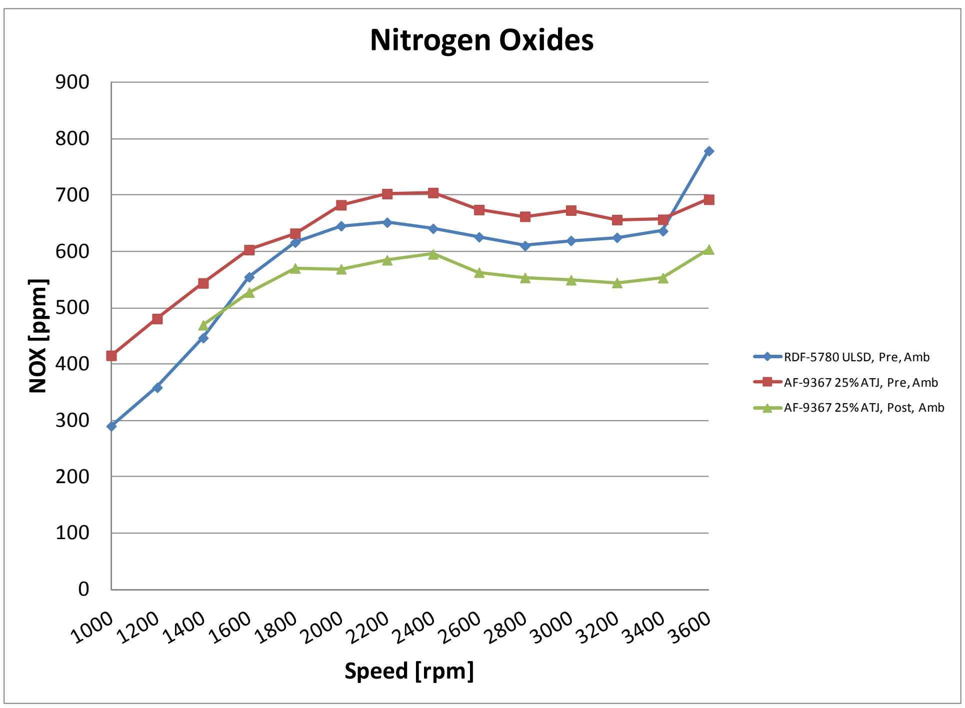

Figure 12. GEP 6.5L(T) Raw Emissions – NOX

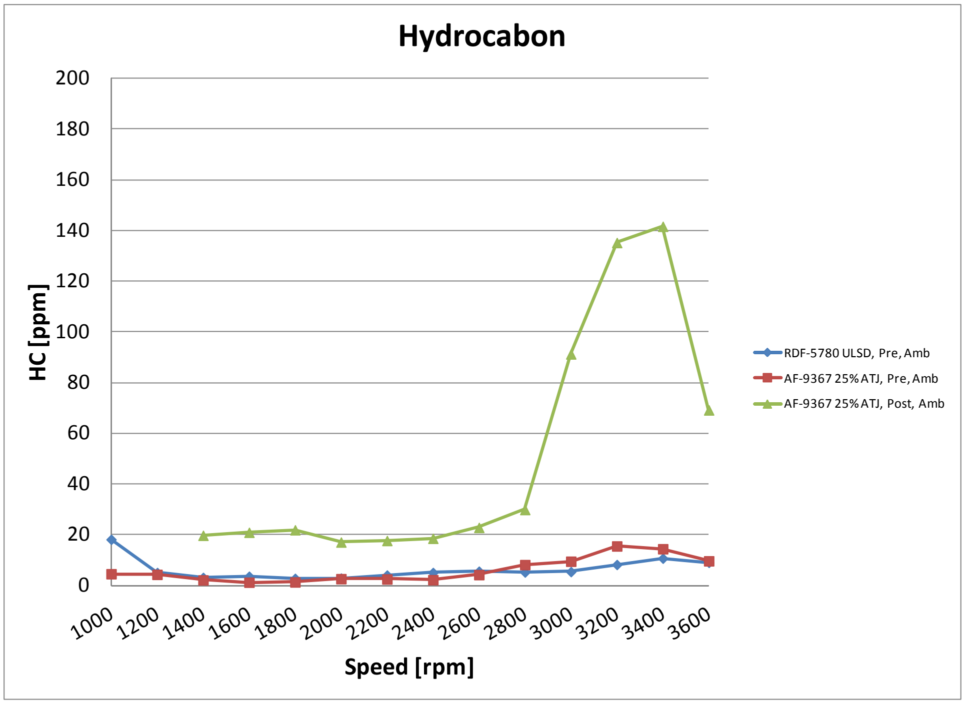

Figure 13. GEP 6.5L(T) Raw Emissions - HC

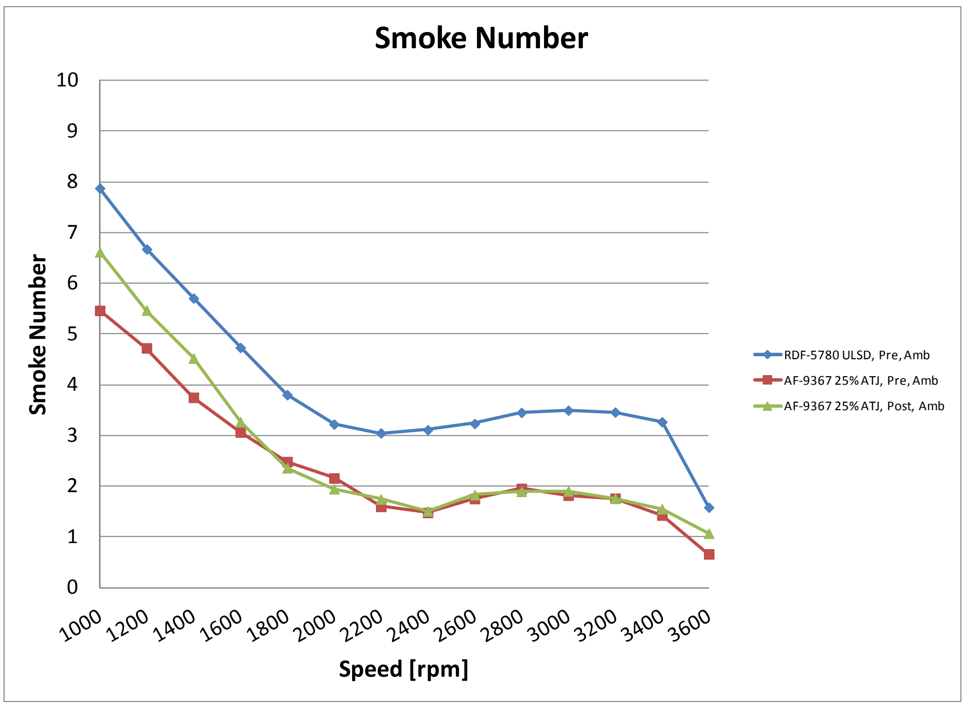

Figure 14. GEP 6.5L(T) Raw Emissions - Smoke

7.2.3 Cylinder Pressure Analysis

Instrumentation

For high speed cylinder pressure analysis, the number 2 cylinder was instrumented on the GEP 6.5L(T) engine. This was done because it was both closest to the front of the engine where the shaft encoder was mounted, and because the high pressure fuel line (exiting the injection pump) was more accessible than the Number 1 cylinder line. Figure 15 shows the location of the fuel line pressure transducer located at the outlet of the fuel injection pump.

Figure 15. Injection Line Pressure Transducer (GEP 6.5L(T))

Figure 16 shows the location in the head of the pre-chamber pressure transducer (which uses the glow plug port) and the instrumented fuel injector. This GEP 6.5L(T) engine was not instrumented for the main chamber cylinder pressure for this testing. The fuel injector was instrumented for needle lift.

Figure 16. GEP 6.5L(T) Cylinder Pressure Transducers and Instrumented Injector

GEP 6.5L(T) Engine operating on 25% ATJ Blend

Data presented in Table 10 through Table 12, and the subsequent heat release plots are calculated from the pre-chamber pressure transducer. The following discussion refers only to the full load power curve data point plots that reflect peak torque and peak power speeds. All additional power curve data plots are available in APPENDIX A.

Table 10. GEP6.5L(T) Full Load Power Curve Combustion Parameters, 1000 to 1800 RPM

Fuel:	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post
Run#:	860	874	888	861	875	889	862	876	890	863	877	891	864	878	892
Cylinder Name	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC
Engine Rpm	1000	1000	1000	1200	1200	1200	1400	1400	1400	1600	1600	1600	1800	1800	1800
MaxPress (bar)	95.72	89.48	85.67	104.67	95.50	94.90	108.22	99.11	98.20	116.01	106.25	106.37	117.99	110.74	110.42
MaxPressPos (°ATDC)	5.2	5.4	5.2	5.4	6.6	6.6	7.4	5.6	6	6.6	7.4	7.6	7.4	8.4	8.6
MaxPressRise (bar/°)	5.373	5.483	5.525	5.805	5.790	5.922	4.940	5.122	5.085	4.467	4.612	4.237	4.047	3.649	3.807
MaxPressRisePos (°ATDC)	-4.0	-2.8	-2.2	-2.8	-1.4	-1.2	-1.0	0.0	0.6	0.2	1.4	1.4	0.4	1.8	2.0
Peg (bar)	1.036	1.015	1.061	1.015	1.012	1.018	1.008	1.005	0.998	1.010	1.004	1.038	1.006	1.002	1.035
Indicated Power (kW)	5.812	5.277	5.243	7.872	7.037	7.107	9.946	8.922	8.980	12.282	10.850	11.235	14.174	12.912	13.233
gIMEP (bar)	7.219	6.734	6.643	8.268	7.532	7.584	9.053	8.211	8.297	9.888	8.811	9.086	10.231	9.390	9.589
nIMEP (bar)	8.722	7.941	7.862	9.826	8.795	8.862	10.636	9.535	9.581	11.474	10.126	10.473	11.748	10.696	10.952
pIMEP (bar)	1.503	1.208	1.219	1.558	1.262	1.278	1.582	1.324	1.284	1.586	1.315	1.387	1.517	1.306	1.362
MaxCumHeat (kJ)	1.200	1.047	1.053	1.297	1.129	1.152	1.388	1.213	1.218	1.441	1.263	1.313	1.462	1.329	1.365
MaxHeatRel (J/°)	68.84	74.90	78.19	82.12	85.19	87.62	80.43	81.34	83.83	80.28	84.79	85.78	76.02	82.30	85.01
SOCAng (°ATDC)	-10.0	-9.4	-9.0	-9.4	-8.8	-8.6	-8.6	-8.0	-7.4	-8.0	-7.0	-7.0	-7.8	-6.6	-6.4
EOCAng (°ATDC)	86.6	66.2	80.8	87.4	69.0	64.4	69.4	65.0	59.8	67.6	54.0	51.2	63.8	42.4	44.4
MFB 02Angle (°ATDC)	-7.55	-6.35	-5.78	-6.98	-5.59	-5.51	-6.06	-4.84	-4.45	-5.73	-4.08	-4.17	-5.50	-3.83	-3.72
MFB 10Angle (°ATDC)	-4.53	-4.05	-3.33	-3.50	-2.78	-2.39	-2.11	-1.35	-0.68	-1.26	0.19	0.36	-0.69	0.78	1.13
MFB 50Angle (°ATDC)	4.79	4.37	5.67	5.04	5.46	5.66	6.86	7.12	7.58	7.57	7.69	8.44	8.49	9.04	9.51
MFB 90Angle (°ATDC)	53.82	41.15	43.19	47.26	37.30	38.98	42.94	32.65	32.49	35.34	30.32	30.83	31.33	28.57	29.90
MFB 0-2 Duration	2.45	3.05	3.22	2.42	3.21	3.09	2.54	3.16	2.95	2.27	2.92	2.83	2.30	2.77	2.68
MFB 0-10 Duration	5.47	5.35	5.67	5.90	6.02	6.21	6.49	6.65	6.72	6.74	7.19	7.36	7.11	7.38	7.53
MFB 0-50 Duration	14.79	13.77	14.67	14.44	14.26	14.26	15.46	15.12	14.98	15.57	14.69	15.44	16.29	15.64	15.91
MFB 2-10 Duration	3.02	2.29	2.45	3.49	2.81	3.12	3.95	3.49	3.77	4.47	4.27	4.54	4.80	4.61	4.85
MFB 10-90 Duration	58.35	45.20	46.52	50.76	40.08	41.37	45.04	34.01	33.17	36.60	30.13	30.46	32.03	27.79	28.78
gIMEPAvg (bar)	7.219	6.734	6.643	8.268	7.532	7.584	9.053	8.211	8.297	9.888	8.811	9.086	10.231	9.390	9.589
gIMEPSTD (bar)	0.087	0.074	0.117	0.101	0.068	0.090	0.095	0.056	0.087	0.109	0.087	0.070	0.105	0.071	0.093
gIMEPCOV (%)	1.203	1.106	1.762	1.227	0.901	1.181	1.053	0.680	1.052	1.105	0.988	0.769	1.028	0.758	0.967
SOI Timing 1 (°ATDC)	-10.2	-9.6	-9.2	-9.6	-9.0	-8.8	-8.8	-8.2	-7.6	-8.2	-7.2	-7.2	-8.0	-6.8	-6.6
SOI Timing 2 (°ATDC)	0.0	0.0	0.0	0.0	0.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.8	32.0
EOI Timing 1 (°ATDC)	12.6	12.6	13.2	12.6	13.2	13.8	13.8	14.4	14.8	13.4	14.0	14.2	14.8	16.0	16.0
EOI Timing 2 (°ATDC)	0.0	0.0	0.0	0.0	0.0	25.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.4	33.8
Start Injection(NeedleLift) #1	-10.2	-9.6	-9.2	-9.6	-9.0	-8.8	-8.8	-8.2	-7.6	-8.2	-7.2	-7.2	-8.0	-6.8	-6.6
End Injection(NeedleLift) #1	12.6	12.6	13.2	12.6	13.2	13.8	13.8	14.4	14.8	13.4	14.0	14.2	14.8	16.0	16.0
Start Injection(NeedleLift) #2	0.0	0.0	0.0	0.0	0.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.8	32.0
End Injection(NeedleLift) #2	0.0	0.0	0.0	0.0	0.0	25.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.4	33.8

Table 11. GEP6.5L(T) Full Load Power Curve Combustion Parameters, 2000 to 2800 RPM

Fuel:	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post
Run#:	865	879	893	866	880	894	867	881	895	868	882	896	869	883	897
Cylinder Name	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC
Engine Rpm	2000	2000	2000	2200	2200	2200	2400	2400	2400	2600	2600	2600	2800	2800	2800
MaxPress (bar)	122.12	113.41	111.07	121.70	111.63	108.31	118.90	109.87	107.76	116.77	106.87	101.65	113.38	103.42	99.74
MaxPressPos (°ATDC)	7.8	8.8	9.2	8.2	9.6	9.8	8.6	10.0	10.0	8.2	10.0	10.0	7.6	8.2	8.2
MaxPressRise (bar/°)	3.858	3.386	3.227	3.927	3.260	3.211	4.006	3.255	3.171	3.916	3.230	3.018	3.624	3.104	3.043
MaxPressRisePos (°ATDC)	0.4	2.2	2.4	0.8	-13.2	-13.0	1.0	-9.6	-9.6	0.6	-10.4	-10.2	0.8	-10.4	-10.4
Peg (bar)	1.004	1.004	1.025	1.007	1.005	1.026	1.007	1.004	1.031	1.008	1.005	1.033	1.009	1.012	1.048
Indicated Power (kW)	16.097	14.691	14.815	17.945	15.961	16.279	19.011	17.503	17.512	20.242	19.036	18.789	21.459	20.085	19.914
gIMEP (bar)	10.580	9.714	9.743	10.814	9.783	9.884	10.607	9.908	9.867	10.541	10.014	9.819	10.451	9.924	9.761
nIMEP (bar)	11.995	10.943	11.025	12.145	10.838	11.006	11.787	10.877	10.847	11.578	10.915	10.739	11.385	10.685	10.563
pIMEP (bar)	1.415	1.230	1.282	1.331	1.055	1.122	1.180	0.969	0.981	1.037	0.901	0.920	0.934	0.761	0.802
MaxCumHeat (kJ)	1.500	1.380	1.396	1.553	1.408	1.424	1.530	1.423	1.443	1.532	1.453	1.455	1.543	1.451	1.455
MaxHeatRel (J/°)	74.56	82.55	82.30	77.43	80.31	76.66	74.04	73.95	74.44	68.46	69.05	64.59	65.71	63.62	60.15
SOCAng (°ATDC)	-7.8	-6.4	-6.0	-7.6	-6.0	-5.8	-7.8	-6.0	-6.2	-8.6	-6.6	-6.6	-8.4	-6.4	-6.2
EOCAng (°ATDC)	47.0	43.2	45.0	47.2	43.4	50.0	50.6	46.6	48.8	55.2	50.0	54.2	57.8	53.6	59.4
MFB 02Angle (°ATDC)	-5.58	-3.72	-3.25	-5.48	-3.48	-3.21	-5.70	-3.64	-3.68	-6.41	-4.08	-3.77	-6.38	-3.97	-3.84
MFB 10Angle (°ATDC)	-0.68	1.16	1.65	-0.48	1.65	2.06	-0.62	1.55	1.69	-1.75	1.16	1.42	-2.18	0.62	1.07
MFB 50Angle (°ATDC)	8.59	9.53	10.45	9.11	10.49	11.44	8.89	10.67	10.94	8.57	10.80	11.64	8.89	10.99	12.17
MFB 90Angle (°ATDC)	30.46	28.68	30.77	31.85	29.75	31.69	33.56	31.36	33.61	36.35	33.91	36.66	38.18	35.45	38.84
MFB 0-2 Duration	2.22	2.68	2.75	2.12	2.52	2.59	2.10	2.36	2.52	2.19	2.52	2.83	2.02	2.43	2.36
MFB 0-10 Duration	7.12	7.56	7.65	7.12	7.65	7.86	7.18	7.55	7.89	6.85	7.76	8.02	6.22	7.02	7.27
MFB 0-50 Duration	16.39	15.93	16.45	16.71	16.49	17.24	16.69	16.67	17.14	17.17	17.40	18.24	17.29	17.39	18.37
MFB 2-10 Duration	4.90	4.89	4.90	5.00	5.13	5.28	5.08	5.20	5.36	4.66	5.24	5.19	4.20	4.58	4.91
MFB 10-90 Duration	31.13	27.51	29.12	32.34	28.09	29.63	34.18	29.81	31.92	38.10	32.75	35.24	40.36	34.84	37.78
gIMEPAvg (bar)	10.580	9.714	9.743	10.814	9.783	9.884	10.607	9.908	9.867	10.541	10.014	9.819	10.451	9.924	9.761
gIMEPSTD (bar)	0.120	0.087	0.082	0.110	0.099	0.112	0.105	0.105	0.086	0.135	0.085	0.106	0.104	0.091	0.108
gIMEPCOV (%)	1.131	0.898	0.845	1.019	1.013	1.132	0.986	1.062	0.875	1.278	0.849	1.075	0.997	0.917	1.110
SOI Timing 1 (°ATDC)	-8.0	-6.6	-6.2	-7.8	-6.2	-6.0	-8.0	-6.2	-6.4	-8.8	-6.8	-6.8	-8.6	-6.6	-6.4
SOI Timing 2 (°ATDC)	0.0	33.6	34.0	0.0	21.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
EOI Timing 1 (°ATDC)	16.2	18.2	18.0	18.4	20.2	20.2	19.4	21.0	21.0	18.8	18.6	19.0	17.2	20.2	19.8
EOI Timing 2 (°ATDC)	0.0	37.8	38.2	0.0	21.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Start Injection(NeedleLift) #1	-8.0	-6.6	-6.2	-7.8	-6.2	-6.0	-8.0	-6.2	-6.4	-8.8	-6.8	-6.8	-8.6	-6.6	-6.4
End Injection(NeedleLift) #1	16.2	18.2	18.0	18.4	20.2	20.2	19.4	21.0	21.0	18.8	18.6	19.0	17.2	20.2	19.8
Start Injection(NeedleLift) #2	0.0	33.6	34.0	0.0	21.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
End Injection(NeedleLift) #2	0.0	37.8	38.2	0.0	21.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 12. GEP6.5L(T) Full Load Power Curve Combustion Parameters, 3000 to 3600 RPM

Fuel:	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post	ULSD-Pre	ATJ-Pre	ATJ-Post
Run#:	870	884	898	871	885	899	872	886	900	873	887	901
Cylinder Name	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC	Cyl-2_PC
Engine Rpm	3000	3000	3000	3200	3200	3200	3400	3400	3400	3600	3600	3600
MaxPress (bar)	112.76	103.20	97.57	110.23	101.28	96.91	110.08	99.95	95.76	100.50	91.90	91.92
MaxPressPos (°ATDC)	7.4	8.4	8.4	7.0	7.6	8.2	6.6	8.0	8.2	6.8	8.2	8.0
MaxPressRise (bar/°)	3.738	3.061	2.939	3.654	3.106	2.963	3.411	3.103	3.012	2.954	2.931	2.902
MaxPressRisePos (°ATDC)	0.2	-10.8	-10.2	0.6	-11.4	-11.2	0.2	-11.2	-11.0	-12.0	-10.4	-10.4
Peg (bar)	1.006	1.027	1.076	1.012	1.021	1.232	1.012	1.029	1.252	1.017	1.017	1.122
Indicated Power (kW)	22.537	21.098	20.718	23.815	22.313	22.060	24.825	23.263	23.117	21.178	19.605	20.684
gIMEP (bar)	10.347	9.869	9.574	10.382	9.849	9.594	10.463	9.926	9.695	9.238	8.619	8.946
nIMEP (bar)	11.158	10.469	10.252	11.049	10.374	10.231	11.060	10.364	10.298	9.434	8.734	9.214
pIMEP (bar)	0.812	0.600	0.678	0.667	0.525	0.637	0.596	0.437	0.603	0.197	0.115	0.268
MaxCumHeat (kJ)	1.538	1.441	1.439	1.538	1.434	1.450	1.555	1.444	1.479	1.328	1.210	1.317
MaxHeatRel (J/°)	65.08	59.44	56.15	65.19	61.77	55.86	61.56	56.76	53.70	58.22	54.37	50.01
SOCAng (°ATDC)	-8.4	-6.4	-5.8	-8.2	-6.2	-6.0	-8.0	-6.0	-5.6	-7.2	-5.4	-5.8
EOCAng (°ATDC)	63.6	56.8	60.4	62.0	55.8	63.6	64.8	61.6	68.8	57.6	57.2	67.8
MFB 02Angle (°ATDC)	-6.36	-3.96	-3.20	-6.22	-3.97	-3.44	-6.25	-3.85	-3.30	-5.55	-3.44	-3.65
MFB 10Angle (°ATDC)	-2.20	0.45	1.25	-1.61	0.98	1.65	-1.87	0.92	1.81	-1.52	1.26	0.98
MFB 50Angle (°ATDC)	8.80	10.99	12.60	9.58	11.75	13.02	10.10	12.52	14.65	9.55	11.92	13.00
MFB 90Angle (°ATDC)	40.38	36.65	39.90	41.14	37.51	41.00	42.05	38.98	43.64	35.61	33.49	39.82
MFB 0-2 Duration	2.04	2.44	2.60	1.98	2.23	2.56	1.75	2.15	2.30	1.65	1.96	2.15
MFB 0-10 Duration	6.20	6.85	7.05	6.59	7.18	7.65	6.13	6.92	7.41	5.68	6.66	6.78
MFB 0-50 Duration	17.20	17.39	18.40	17.78	17.95	19.02	18.10	18.52	20.25	16.75	17.32	18.80
MFB 2-10 Duration	4.16	4.41	4.44	4.62	4.95	5.08	4.38	4.78	5.11	4.03	4.70	4.63
MFB 10-90 Duration	42.58	36.20	38.65	42.74	36.53	39.35	43.92	38.06	41.83	37.13	32.23	38.84
gIMEPAvg (bar)	10.347	9.869	9.574	10.382	9.849	9.594	10.463	9.926	9.695	9.238	8.619	8.946
gIMEPSTD (bar)	0.134	0.136	0.144	0.109	0.095	0.131	0.142	0.098	0.107	0.140	0.093	0.125
gIMEPCOV (%)	1.298	1.382	1.503	1.047	0.962	1.368	1.359	0.992	1.104	1.519	1.077	1.401
SOI Timing 1 (°ATDC)	-8.6	-6.6	-6.0	-8.4	-6.4	-6.2	-8.2	-6.2	-5.8	-7.4	-5.6	-6.0
SOI Timing 2 (°ATDC)	20.8	0.0	0.0	0.0	0.0	0.0	0.0	52.4	0.0	0.0	48.0	48.4
EOI Timing 1 (°ATDC)	20.2	22.6	24.4	22.2	24.2	24.2	24.4	26.4	26.4	24.8	24.8	26.8
EOI Timing 2 (°ATDC)	21.6	0.0	0.0	0.0	0.0	0.0	0.0	53.4	0.0	0.0	51.4	54.0
Start Injection(NeedleLift) #1	-8.6	-6.6	-6.0	-8.4	-6.4	-6.2	-8.2	-6.2	-5.8	-7.4	-5.6	-6.0
End Injection(NeedleLift) #1	20.2	22.6	24.4	22.2	24.2	24.2	24.4	26.4	26.4	24.8	24.8	26.8
Start Injection(NeedleLift) #2	20.8	0.0	0.0	0.0	0.0	0.0	0.0	52.4	0.0	0.0	48.0	48.4
End Injection(NeedleLift) #2	21.6	0.0	0.0	0.0	0.0	0.0	0.0	53.4	0.0	0.0	51.4	54.0

From the combustion summaries for the full load power curves, the peak pre-chamber pressures for each engine speed and fuel run are shown in Figure 17. At all engine speeds the ULSD pre-test run had the highest peak pressure. The 25% ATJ blend pre and post test runs had similar pressures 2000-RPM and below, but 25% ATJ blend pre-test run exhibited higher pre-chamber pressures above 2000-RPM engine speed. The peak cylinder pressure is ultimately determined by the injection pump metering.

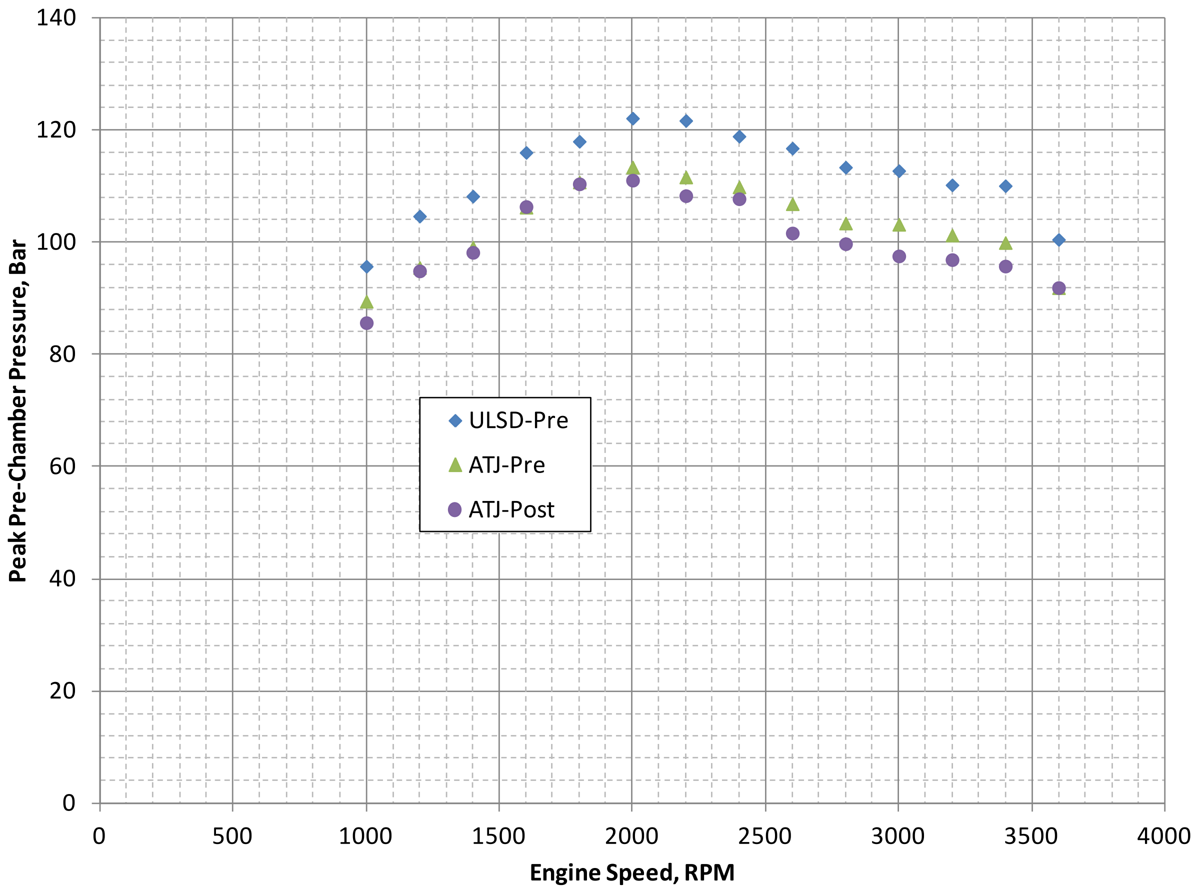

Figure 17. GEP 6.5L(T) Full Load Power Curve Peak Pre-Chamber Pressures

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From the combustion summaries for the full load power curves, the crank angle location of peak pre-chamber pressures for each engine speed and fuel run are shown in Figure 18. At most engine speeds the ULSD pre-test powercurve had the location of peak pressure closest to TDC. The 25% ATJ pre and post test powercurves had similar locations of peak pressure across the speed range, but were retarded approximately 1-degree from the ULSD pre-test runs. A location of peak pressure between 6-8 degrees ATDC corresponds to best engine efficiency. From this data we can surmise that the locations of peak pressure with the 25% ATJ blend was impacted by fuel injection timing changes due to fuel bulk modulus difference.

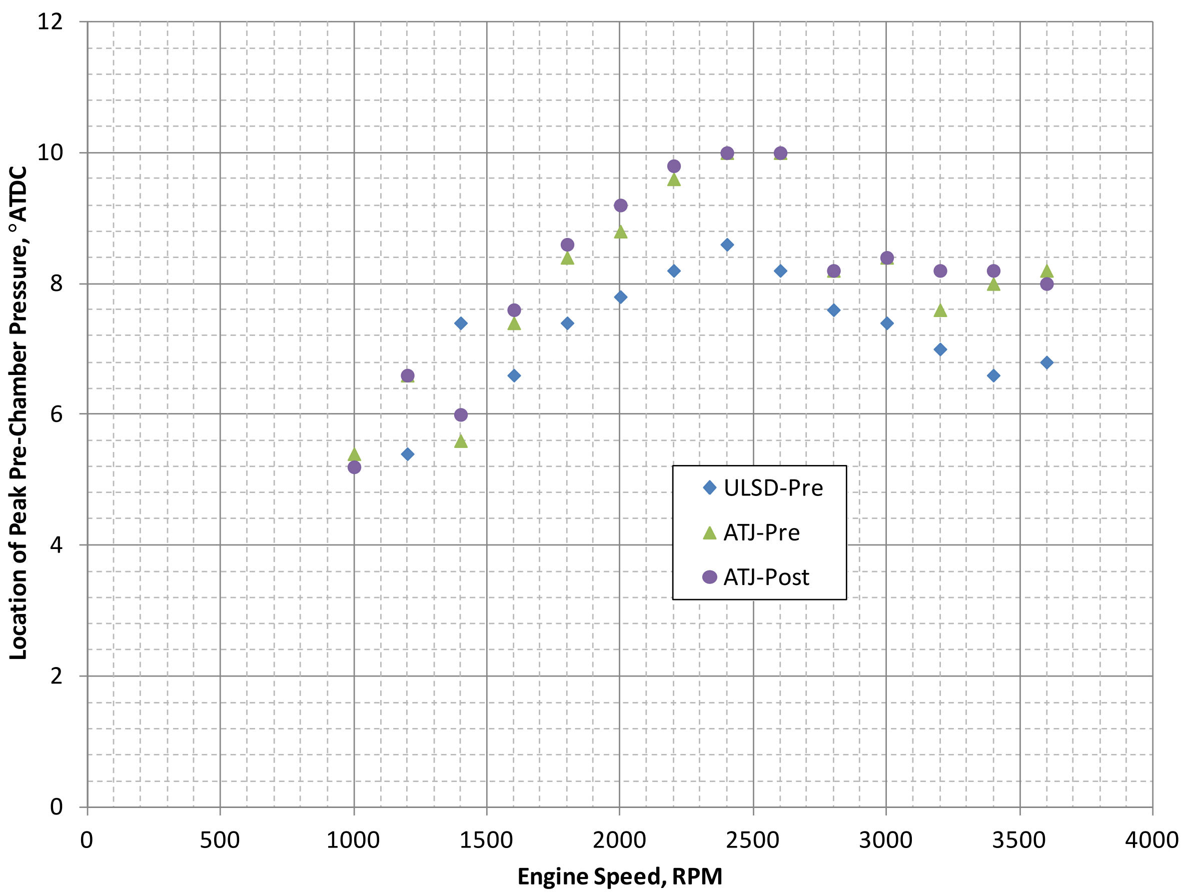

Figure 18. GEP 6.5L(T) Full Load Power Curve Locations of Peak Pre-Chamber Pressure

From the combustion summaries for the full load power curves, the peak rates of pre-chamber pressure rise for each engine speed and fuel run are shown in Figure 19. At the engine speeds below the peak torque speed of 1800-RPM, both ULSD and the 25% ATJ blends had similar peak pressure rise rates. At 2000-RPM and higher, the 25% ATJ pre and power test runs had similar peak pressure rise rates that were lower than the ULSD pre-test rates. The pressure rise rates are affected by the amount of fuel in the cylinder at ignition. Due to the equivalent or lower pressure rise rates, the 25% ATJ blend should not impact overall engine durability.

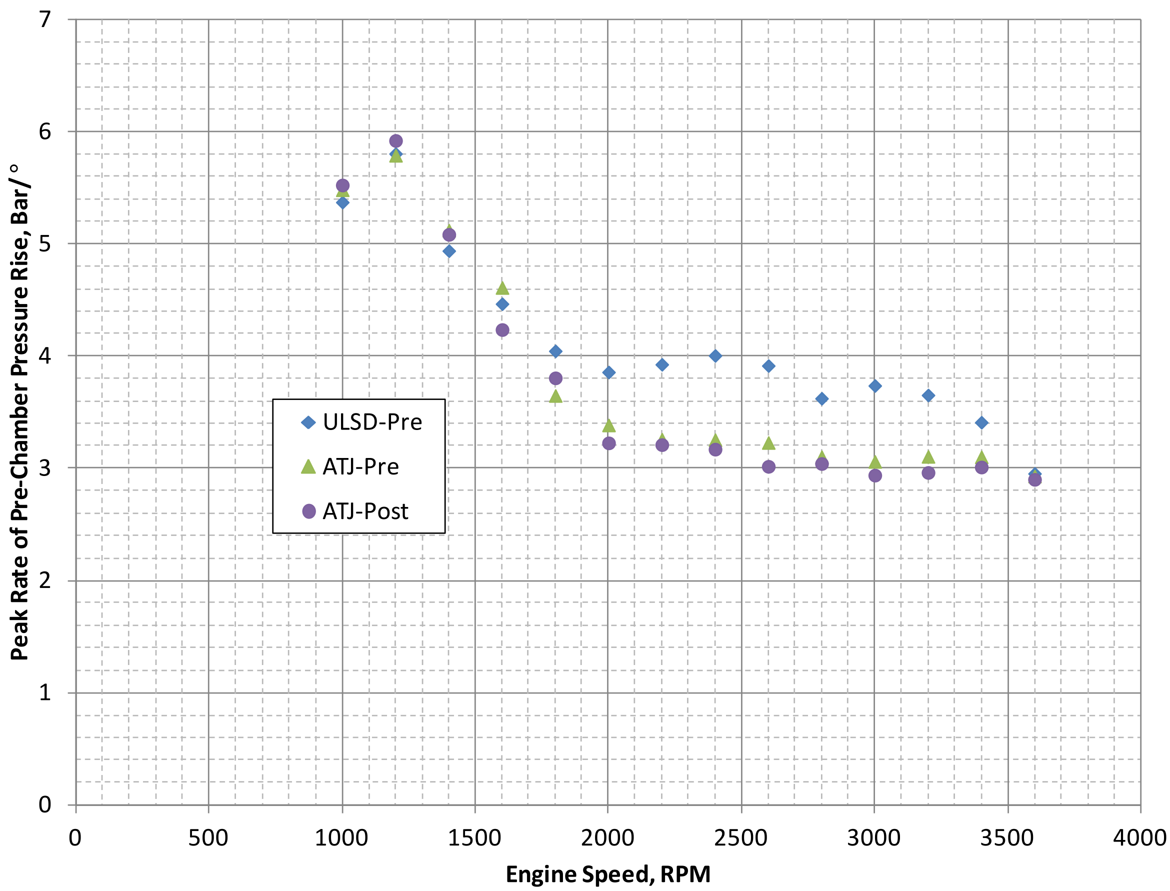

Figure 19. GEP 6.5L(T) Full Load Power Curve Peak Rate of Pre-Chamber Pressure Rise

From the combustion summaries for the full load power curves, the peak heat release rates for each engine speed and fuel run are shown in Figure 20. At the engine speeds below the engine speed of 2000-RPM, both 25% ATJ blend runs had similar peak heat release rates that were marginally greater than the ULSD pre-test run. From 2200-2600-RPM all the fuel runs exhibited similar peak heat release rates. Above 2800-RPM, the 25% ATJ blend runs had similar peak heat release rates that were lower than the ULSD pre-test rates. The peak heat release rates can affect heat transfer. Across the entire speed range the ULSD pre-test run had the most consistent peak heat release rates.

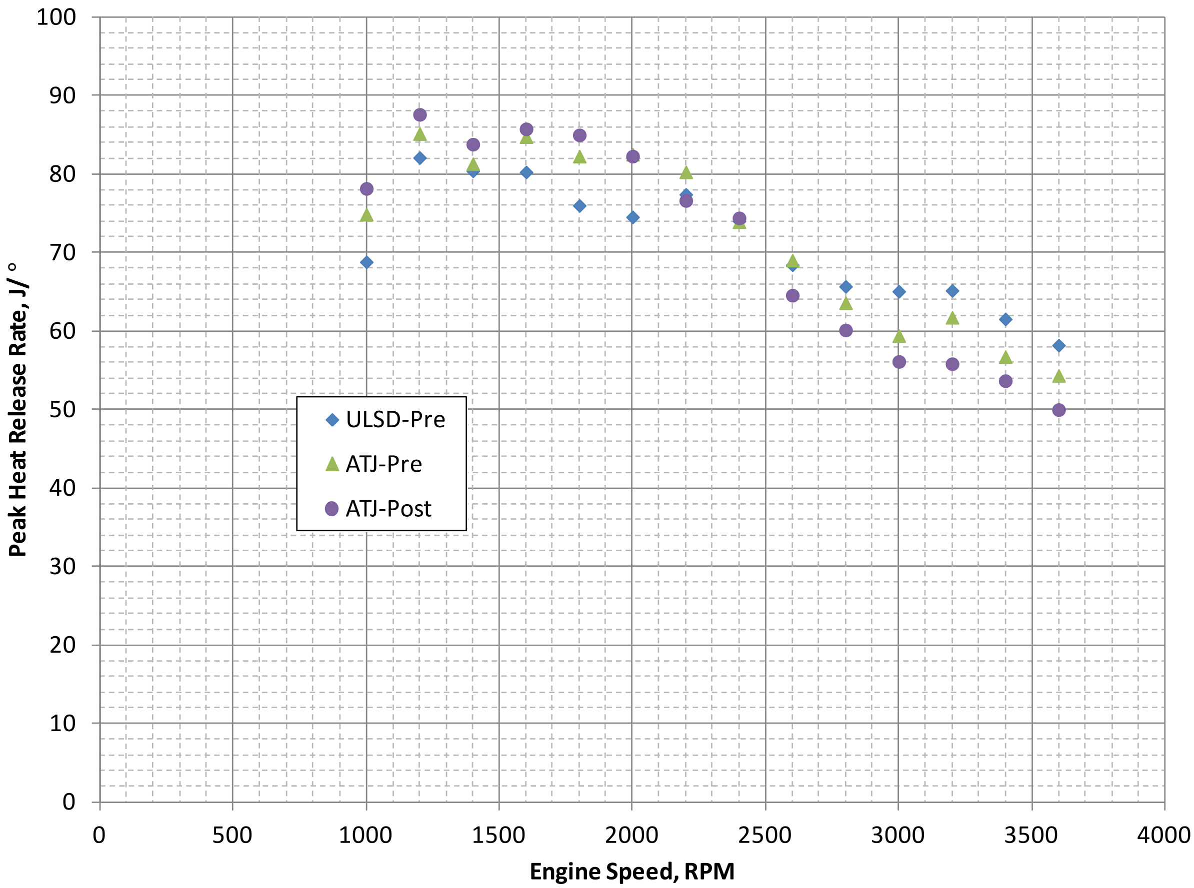

Figure 20. GEP 6.5L(T) Full Load Power Curve Peak Heat Release Rates

From the combustion summaries for the full load power curves, the crank angle location of 50% Mass Fraction Burned (50%MFB) for each engine speed and fuel run are shown in Figure 21. At most engine speeds the ULSD pre-test run had the location of 50%MFB closest to TDC. The 25% ATJ pre and post test runs had similar locations of 50% MFB up to 1800-RPM, and then showed a retarding trend with increased engine speed. The 25% ATJ post-test run exhibited the most retard for the 50%MFB location. The locations of 50%MFB with the 25% ATJ blends were impacted by fuel injection timing retard due to 25% ATJ blends bulk modulus.

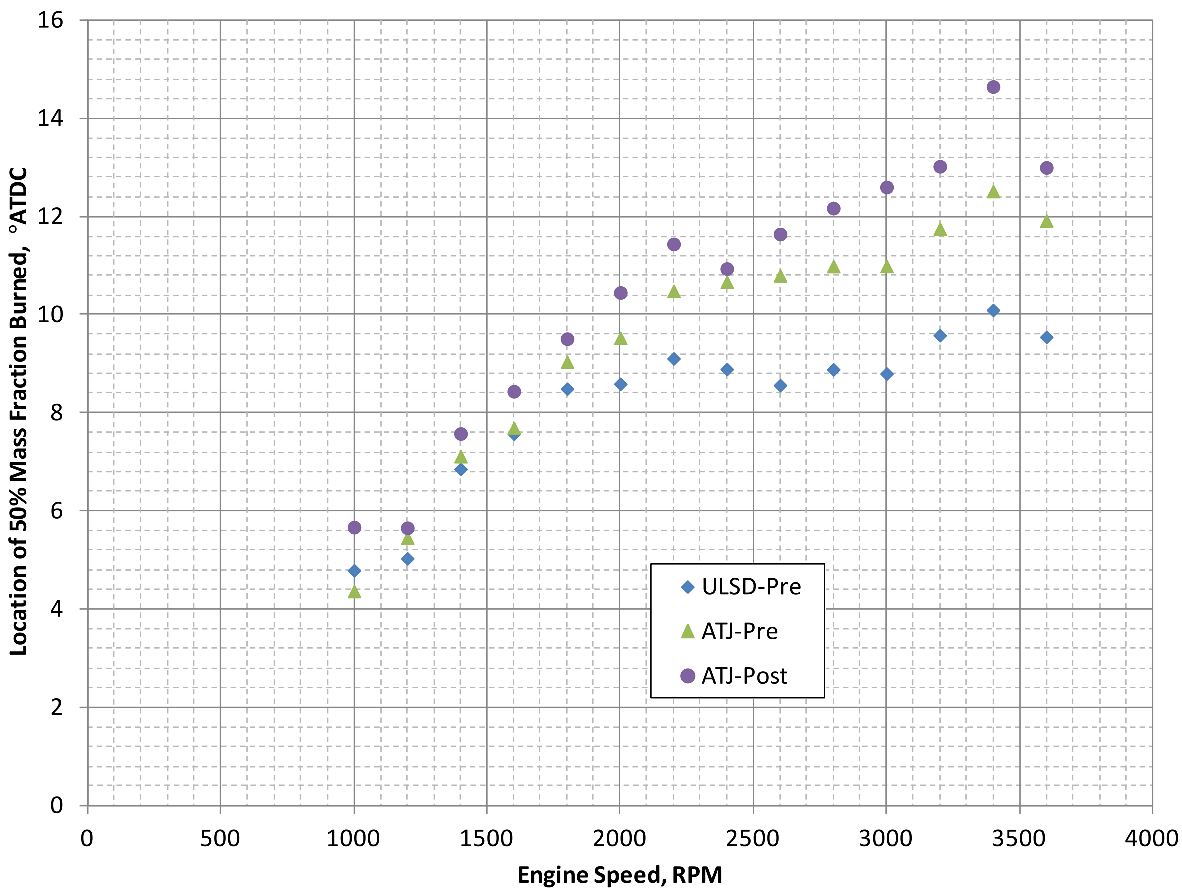

Figure 21. GEP 6.5L(T) Full Load Power Curve Locations of 50% Mass Fraction Burned

From the combustion summaries for the full load power curves, the crank angle interval for the 10-90% Mass Fraction Burned Duration (MFBD) for each engine speed and fuel run are shown in Figure 22. Except at the 3600-RPM engine speed, the ULSD pre-test fuel run exhibited the largest interval of MFBD. The 25% ATJ pre and post test runs had similar MFBD intervals up to 1800-RPM, and then the 25% ATJ post-test MFBD interval started increasing with engine speed. The burn duration would be linked to the injected fuel quantity and fuel volatility. A less volatile fuel should exhibit more diffusion controlled combustion, extending the burn duration.

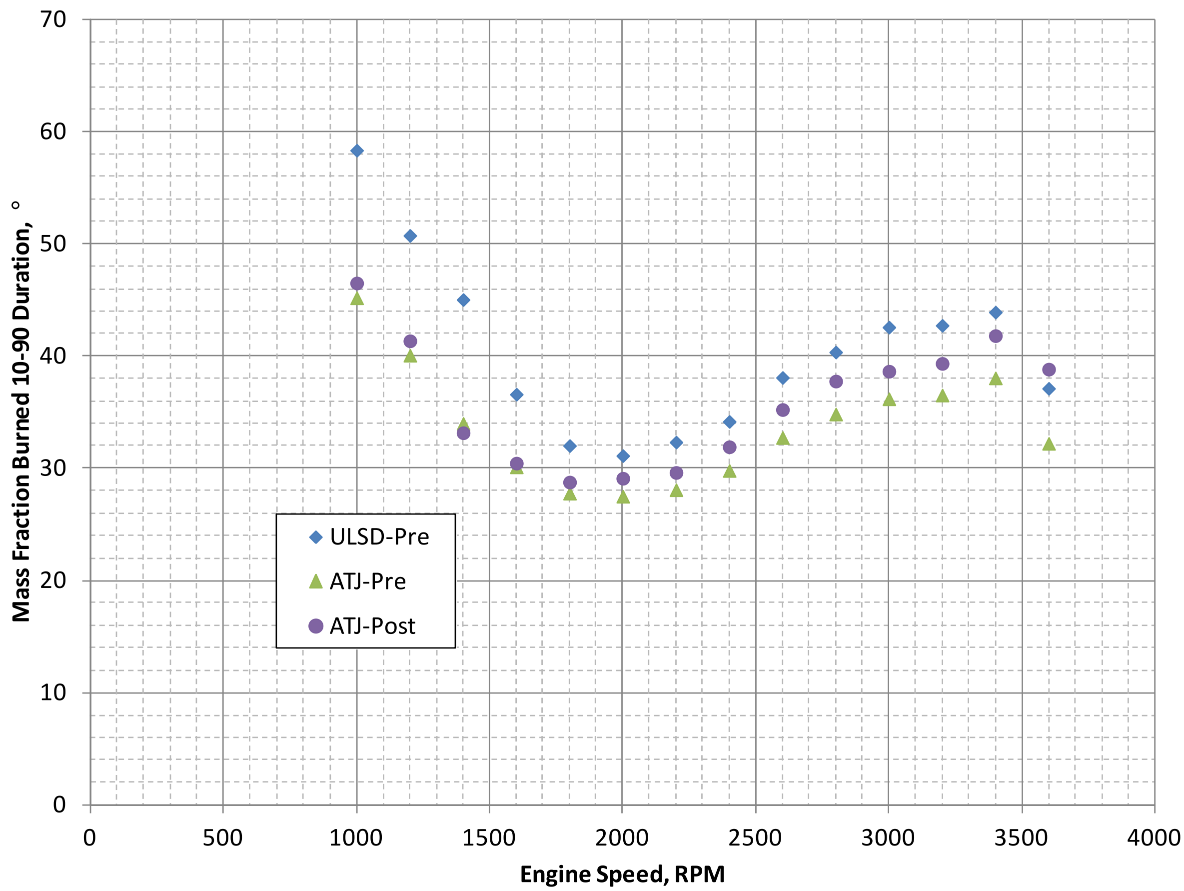

Figure 22. GEP 6.5L(T) Full Load Power Curve 10-90% Mass Fraction Burned Durations

7.3 PEAK POWER AND PEAK TORQUE INDICATOR DIAGRAMS

Figure 23 shows the pre-chamber pressure traces for the GEP 6.5L(T) engine at the rated power condition of 3400-RPM for the ULSD pre-test and the 25% ATJ blend pre and post test fuel runs. The peak pressures are higher with the diesel fuel and the location of peak pressure appears closer to TDC with the diesel fuel. The 25% ATJ pre-test run exhibited higher cylinder pressure than the 25% ATJ post-test run, but the location of peak pressure is similar for the two 25% ATJ runs. Greater energy content and better ignition quality of the diesel fuel accounts for the cylinder pressure differences.

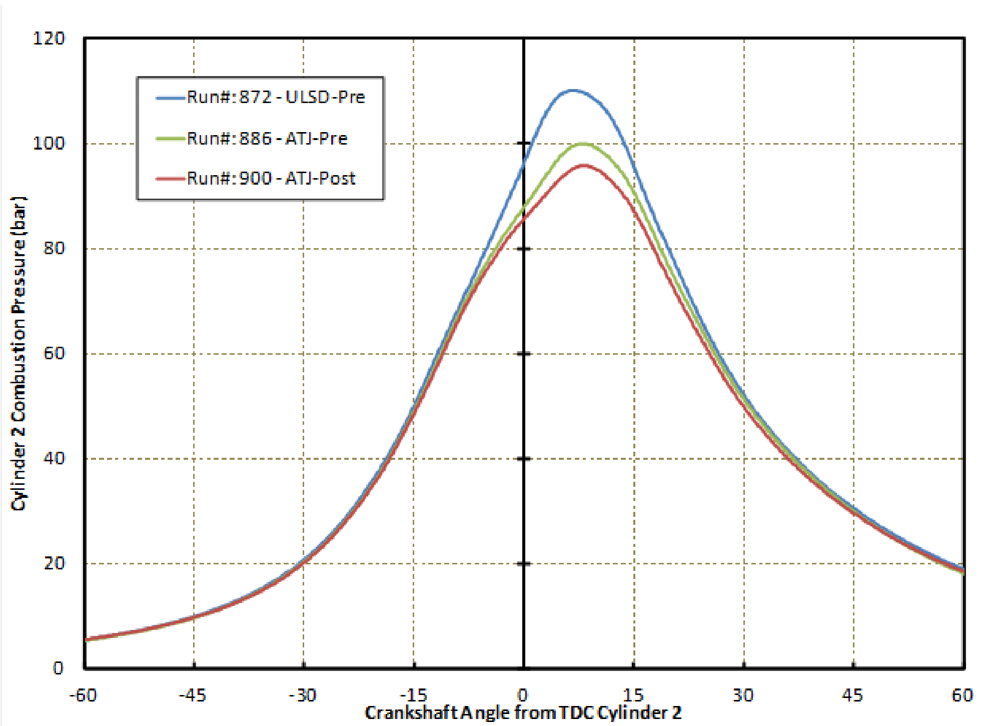

Figure 23. Pre-Chamber Pressure Histories for 3400-RPM and 100% Load

The apparent Heat Release Rates (HRR) calculated from the pre-chamber pressure traces are shown in Figure 24 for the rated speed condition of 3400-RPM for the ULSD pre-test and 25% ATJ pre and post test runs. Included in the plots are the injector needle lift that shows similar start of injection for the 25% ATJ blend runs and advanced injection for the diesel fuel, possibly due to fuel bulk modulus. In the pre-chamber there is very little ignition delay and all fuels appear to start burning within 0.2-degrees of start of injection. The pre and post 25% ATJ blend runs appear to ignite later due to later injection, but exhibit only a slightly faster burn rate. The diesel fuel exhibits a higher maximum HRR. The location of the maximum HRR appears to be retarded with respect to TDC for the two 25% ATJ blend runs. The 25% ATJ post-test run appears to be slightly retarded from the 25% ATJ pre-test run.

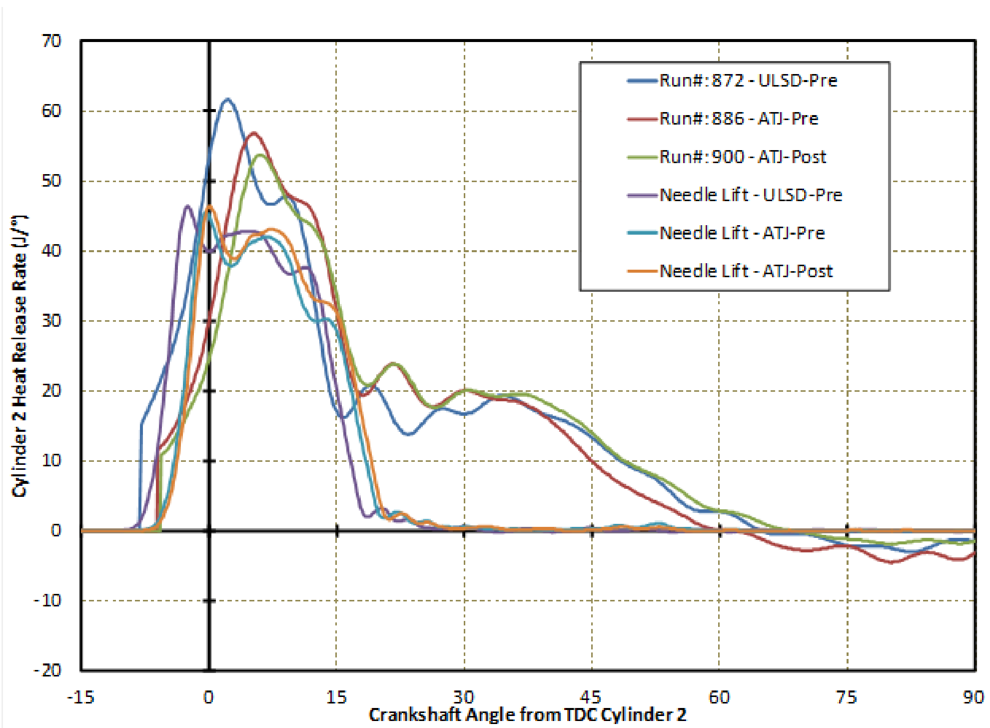

Figure 24. Heat Release Rate Histories for 3400-RPM and 100% Load.

The Mass Fraction Burned (MFB) curve is shown in Figure 25 for the rated power condition for each fuel run. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. The diesel fuel exhibits a faster and earlier initial burn rate, but from 60% MFB and later combustion slows down. The 25% ATJ pre test run exhibits the highest burn rate over the cycle and completes combustion the earliest. The 25% ATJ post test run exhibits a similar slope of diesel fuel up to 50% MFB, then burns like the 25% ATJ pre-test run later in the engine cycle. The start of combustion for the 25% ATJ post test run appears slightly retarded from the 25% ATJ pre test run.

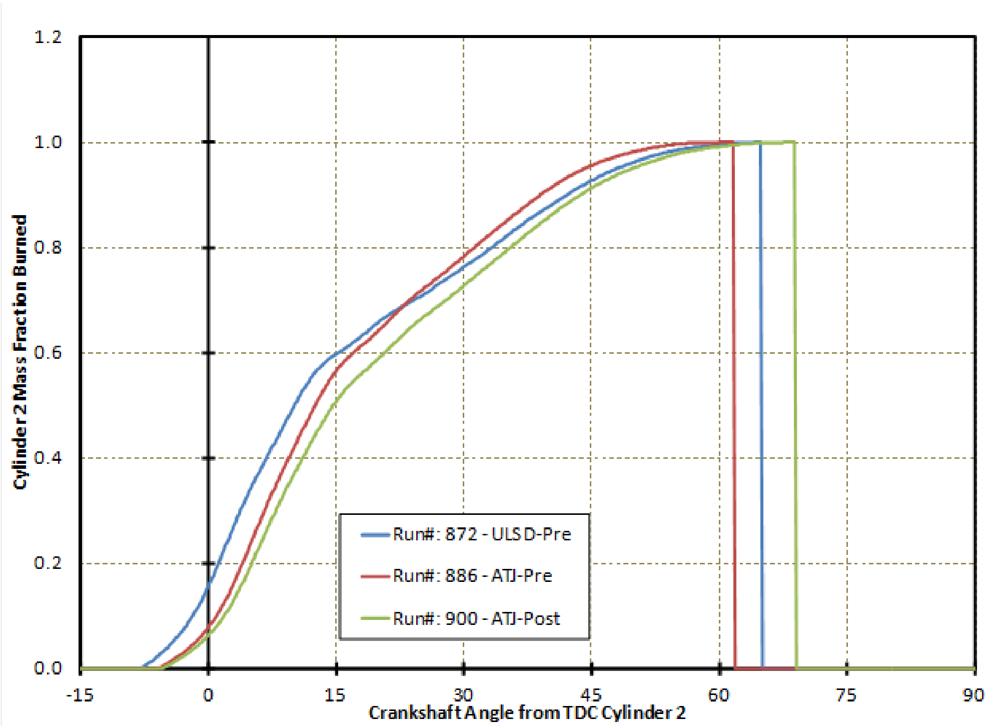

Figure 25. Fuel Mass Fraction Burned for 3400-RPM and 100% Load

Figure 26 shows the pre-chamber pressure traces for the GEP 6.5L(T) engine at the peak torque condition of 1800-RPM for the ULSD pre-test, and 25% ATJ blend pre and post test runs. The peak pressures are higher with the diesel fuel and the location of peak pressure appears closer to TDC with the diesel fuel. The 25% ATJ pre test and the 25% ATJ post test runs had very similar maximum cylinder pressures. The 25% ATJ post test run appears to exhibit a slighlty retarded location of peak pressure. Greater energy content and better ignition quality of the diesel fuel accounts for the cylinder pressure differences at the peak torque speed condition.

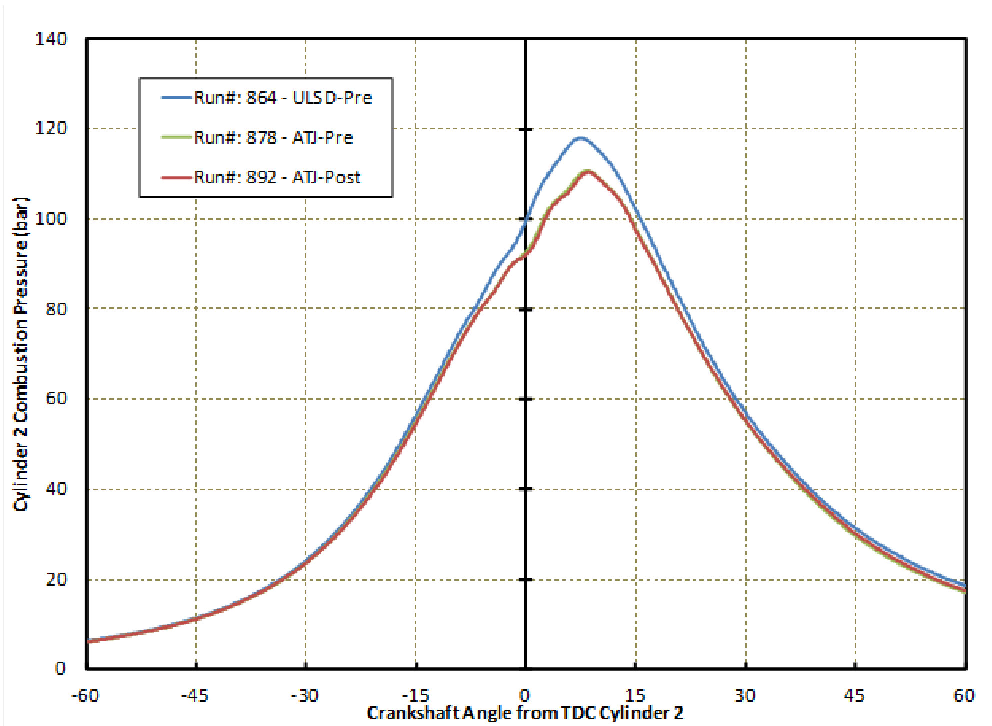

Figure 26. Pre-Chamber Pressure Histories for 1800-RPM and 100% Load

The apparent Heat Release Rates (HRR) calculated from the pre-chamber pressure traces are shown in Figure 27 for the peak torque condition of 1800-RPM for the ULSD pre test, and 25% ATJ blend pre and post test runs. Included in the plots are the injector needle lift that shows similar start of injection for the 25% ATJ blend runs and advanced injection for the diesel fuel, possibly due to fuel bulk modulus. In the pre-chamber there is very little ignition delay and all fuels appear to start burning within 0.2-degrees of start of injection. The pre and post 25% ATJ blend runs appear to ignite later due to later injection, but exhibit a faster burn rate. The 25% ATJ blend fuel runs both exhibits a higher maximum HRR than diesel fuel at peak torque. The location of the maximum HRR appears to be retarded with respect to TDC for the two 25% ATJ blend runs. The 25% ATJ post-test run appears to be slightly retarded from the 25% ATJ pre-test run.

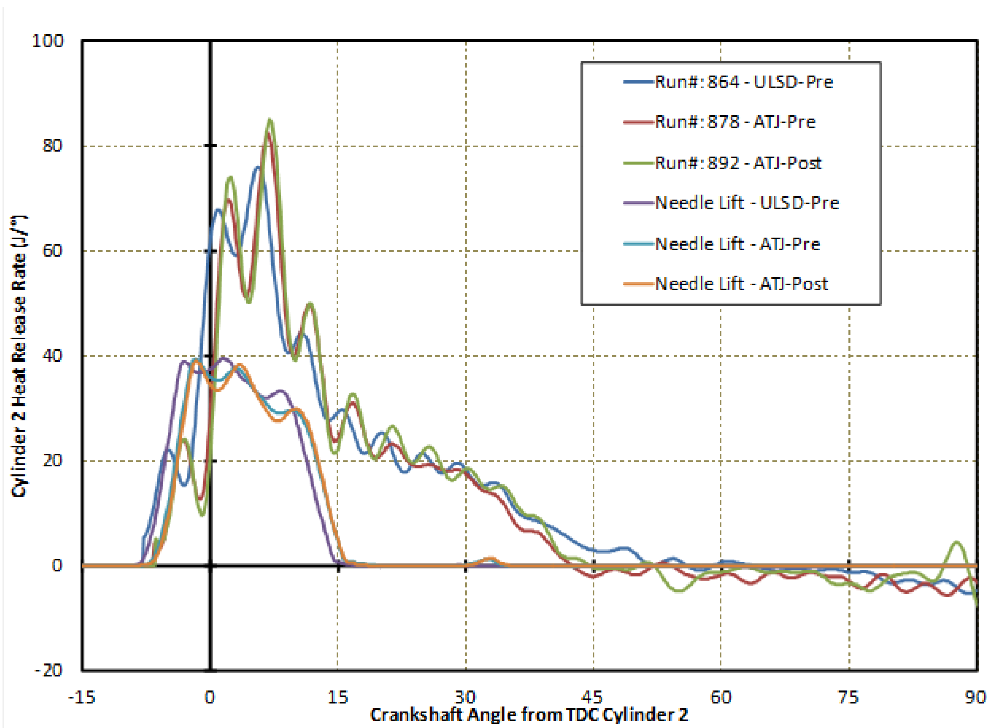

Figure 27. Heat Release Rate Histories for 1800-RPM and 100% Load

The Mass Fraction Burned (MFB) curve is shown in Figure 28 for the peak torque condition for each fuel run. The MFB is the integration of the heat release rate curve from start of combustion, normalized by the maximum cumulative heat release value. The diesel fuel exhibits a slower and earlier initial burn rate, and from 50% MFB and later combustion slows down. The 25% ATJ pre test run exhibits the highest burn rate over the cycle and completes combustion the earliest. The 25% ATJ post test run exhibits a similar slope to the 25% ATJ pre test run up to 50% MFB, then the burn slows and the 25% ATJ post test run finishes later in the engine cycle. The start of combustion for the 25% ATJ post test run appears slightly retarded from the 25% ATJ pre-test run at the peak torque engine condition.

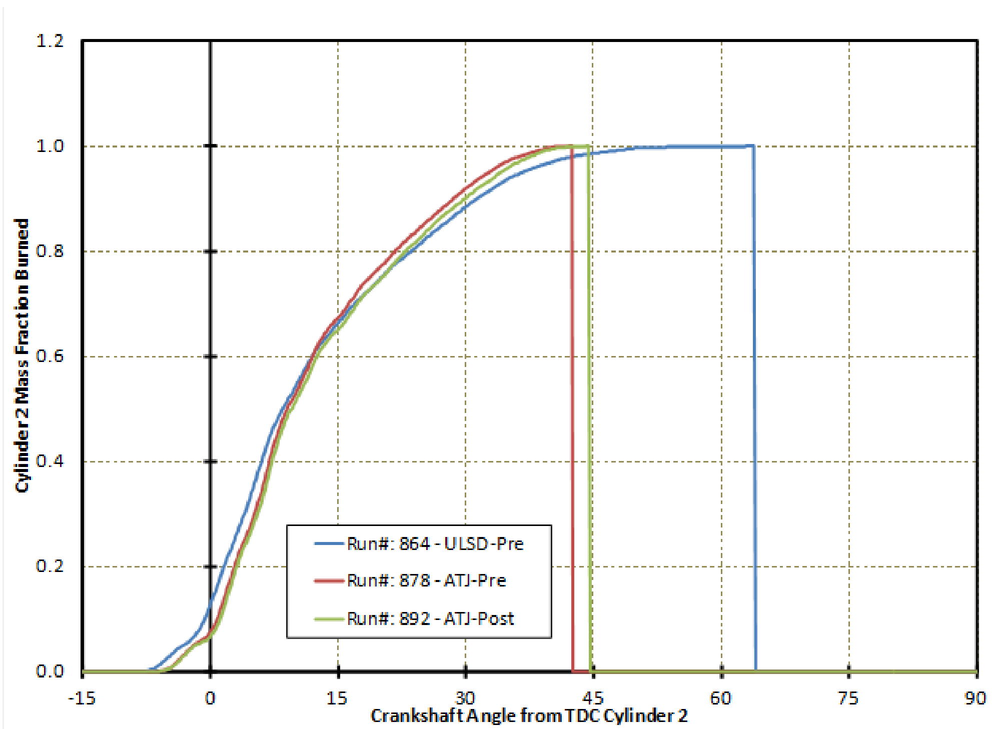

Figure 28. Fuel Mass Fraction Burned for 1800-RPM and 100% Load

7.3.1 210hr Operating Summary

Table 13 shows the engine operating summary for the GEP engine over the 210hr test duration. As per the contract SOW, specifications for the coolant out, fuel inlet, and air inlet temperature were maintained within the desired ranges. Engine output averaged at 183 hp and 283 ft-lb of torque across the 210hr test duration.

Table 13. GEP 6.5L(T) 25% ATJ 210hr Operation Summary

		Rated Conditions (3400 RPM)		Idle Conditions (900 RPM)	
Perameter:	**Units:**	**Average**	**Std. Dev.**	**Average**	**Std. Dev.**
Engine Speed	RPM	3400.00	0.66	900.01	2.41
Torque*	ft*lb	283.73	2.52	32.59	0.41
Fuel Flow	lb/hr	85.37	0.83	4.69	0.19
Power*	bhp	183.68	1.62	5.58	0.08
BSFC*	lb/bhp*hr	0.465	0.005	0.839	0.037
Blow-by	acfm	3.89	0.40	3.14	0.37
Temperatures:					
Coolant In	°F	191.87	0.47	199.81	2.33
Coolant Out	°F	205.00	0.28	203.53	2.30
Oil Gallery	°F	166.86	5.54	199.67	3.98
Oil Sump	°F	235.78	1.50	202.80	3.68
Fuel In	°F	86.01	0.42	86.02	1.99
Fuel Out	°F	119.74	1.40	110.43	3.44
Intake Air (before compressor)	°F	76.96	1.46	77.83	3.26
Intake Air (after compressor)	°F	165.14	1.81	85.75	3.03
Cylinder 1 Exhaust	°F	1272.60	11.07	232.93	7.24
Cylinder 2 Exhaust	°F	1223.06	9.57	249.08	5.92
Cylinder 3 Exhaust	°F	1224.63	9.80	243.36	5.07
Cylinder 4 Exhaust	°F	1251.50	13.70	239.07	5.12
Cylinder 5 Exhaust	°F	1232.74	10.54	231.91	5.85
Cylinder 6 Exhaust	°F	1231.02	9.57	230.00	6.30
Cylinder 7 Exhaust	°F	1204.42	9.80	220.51	4.13
Cylinder 8 Exhaust	°F	1193.26	15.94	224.22	4.32
Pressures:					
Oil Galley	psi	49.45	1.29	20.31	1.68
Ambient Pressure	psiA	14.27	0.11	14.27	0.11
Boost Pressure	psi	4.45	0.10	0.09	0.02
Intake Restriction	psi	0.26	0.01	0.04	0.01
Exhaust Restriction	psi	0.35	0.01	-0.05	0.01
Coolant System	psi	11.77	0.81	7.03	0.69

* Non-corrected Values

Oil addition and subtraction data for the 210hr test duration is shown in Table 14. Overall oil consumption appeared to increase across the test duration, with total test oil consumption rate measuring at 0.12 lbs/hr, approximately twice that of historical data using the GEP engine and MIL-PRF-2104H 15W40 oil [6].

Table 14. GEP 6.5L(T) 25% ATJ Oil Additions/Subtraction Data

GEP 6.5L(T) Accelerated 210hr Durability Test Lubricant Additions/Subtractions

Lubricant No.	LO288074	Project No.	20639.01.320

Initial Fill: (engine test)

	Date	Lubricant + Container Weight, lbs	-	Container Weight,lbs	=	Lubricant Weight, lbs
	12/8/2015		-			14.74
	Dry Filter = 0.73		-		=	
				Total Initial Fill		14.74

126-hr Oil Drain:

	Date	Lubricant + Container Weight, lbs	-	Container Weight,lbs	=	Lubricant Weight, lbs
	12/15/2015		-		=	8.6
	filter (wet/dry)	1.72	-	0.73	=	0.99
			-	Total 126-Hour Drain		9.59

126-hr Oil Fill:

		Lubricant + Container Weight, lbs	-	Container Weight,lbs	=	Lubricant Weight, lbs
			-		=	8.6
	Dry Filter = 0.73		-		=	3.64
				Total 126-Hour Fill		12.24

Samples:

	Date	Sample + Container Weight, lbs	-	Container Weight,lbs	=	Sample Weight, lbs
0-hr	12/9/15	0.26	-	0.05	=	0.21
21-hr	12/10/15	0.26	-	0.05	=	0.21
42-hr	12/11/15	0.24	-	0.05	=	0.19
63-hr	12/12/15	0.30	-	0.05	=	0.25
84-hr	12/13/15	0.31	-	0.05	=	0.26
105-hr	12/14/15	0.30	-	0.05	=	0.25
126-hr	12/15/15	0.30	-	0.05	=	0.25
126-hr**	12/15/15	0.30		0.05	=	0.25
147-hr	12/16/15	0.32	-	0.05	=	0.27
168-hr	12/17/15	0.30	-	0.05	=	0.25
189-hr	12/18/15	0.30	-	0.05	=	0.25
210-hr	12/19/15	0.30	-	0.05	=	0.25
				Total Samples		2.68

Additions:

	Date	Addition + Container Weight, lbs	-	Container Weight,lbs	=	Addition Weight, lbs
21-hr	12/10/15	0.00	-	0.00	=	0.00
42-hr	12/11/15	3.86	-	1.02	=	2.84
63-hr	12/12/15	1.49	-	0.39	=	1.10
84-hr	12/13/15	1.39	-	0.39	=	1.00
105-hr	12/14/15	2.48	-	0.39	=	2.09
126-hr**		***126hr addition combined with 126hr engine oil change*				
147-hr	12/16/15	4.45	-	1.00	=	3.45
168-hr	12/17/15	3.85	-	1.00	=	2.85
189-hr	12/18/15	7.50	-	2.17	=	5.33
210-hr	12/19/15	5.00	-	0.78	=	4.22
				Total Additions		22.88

210-Hour Drain:*

	Date	Lubricant + Container Weight, lbs	-	Container Weight,lbs	=	Lubricant Weight, lbs
	1/5/2016		-		=	12.37
	filter (wet/dry)	1.73	-	0.73	=	1
				Total 210-Hour Drain		13.37

Total Fill [lbs]	26.98
Total Addition [lbs]	22.88
Total Samples [lbs]	2.68
Total Drain [lbs]	22.96
Total 210HR Oil Consumption [lbs]	24.22
Oil Consumption Rate [lbs/hr]	0.12

Table 15 shows the used oil analysis over the 210hr test duration. An oil change was conducted at 126hrs of testing due to poor condition of the MIL-PRF-2104H 15W40 oil (depleted TBN, rapidly climbing TAN, wear metal increases). Overall oil lifespan of the oil charge was consistent with historical testing using this same oil revision [6].

Table 15. GEP 6.5L(T) 25% ATJ Used Oil Analysis

Property	ASTM Test	Test Hours										
		0	21	42	63	84	105	126	147	168	189	210
Viscosity @ 100°C (cSt)	D445	15.5	15.4	16.1	16.5	17.2	18.2	21.3	17.4	18.2	19.1	19.3
Total Base Number (mg KOH/g)	D4739	8.8	6.7	5.4	4.6	3.2	1.9	0.9	4.5	3.3	2.8	2.6
Total Acid Number (mg KOH/g)	D664	2.5	2.9	4.1	6.2	5.6	7.6	10.7	5.3	5.5	7.6	6.9
Oxidation (Abs./cm)	E168 FTNG	0.0	5.0	13.7	18.4	31.6	59.5	100.7	omitted after oil change			
Nitration (Abs./cm)	E168 FTNG	0.0	10.3	16.7	19.5	31.5	45.3	48.6	omitted after oil change			
Soot	Soot	0.2	0.6	1.1	1.4	1.9	2.5	3.3	1.8	2.1	2.6	2.7
Wear Metals (ppm)	D5185											
Al		2	2	3	3	3	4	6	4	5	6	8
Sb		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
B		<1	<1	<1	<1	<1	<1	<1	1	1	2	<1
Ca		2465	2613	2735	2866	2937	3074	3282	2997	3122	3232	3298
Cr		1	3	6	7	9	15	20	14	19	22	22
Cu		2	4	7	7	9	13	21	18	23	27	28
Fe		28	72	114	174	307	680	1149	576	634	718	716
Pb		5	8	13	18	37	100	260	103	106	122	130
Mg		306	324	336	350	363	378	405	367	375	396	404
Mn		1	2	3	3	4	6	9	5	6	6	6
Mo		5	9	13	14	16	22	26	14	17	20	22
Ni		1	3	4	4	5	7	10	5	6	8	8
P		1315	1265	1221	1268	1259	1289	1379	1324	1372	1435	1475
Si		22	40	48	42	44	47	47	22	23	24	23
Ag		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Na		<5	<5	<5	16	20	24	28	15	16	16	18
Sn		3	4	7	8	10	13	18	11	13	16	17
Zn		1421	1457	1501	1585	1632	1708	1847	1695	1746	1839	1882
K		<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
Sr		<1	<1	1	1	1	1	1	1	1	1	1
V		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ti		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cd		<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1

7.3.2 Fuel System Calibration Data

Table 16 shows the pre and post test fuel injection pump calibration data. Parameters measured outside of the specification ranges are shown in red. The primary changes noted in the post test calibration from the pre test measurements was the increase in transfer pressure at mid range engine speeds, and an increase in fuel delivery at 900 rpm pump speed (1800 rpm engine speed). The increase in transfer pump pressure at 1000 rpm pump speed (2000 rpm engine speed) is relatively minor, and could potentially related to some sort of issue with the pressure regulator piston itself (wear debris limiting movement). It is not expected that this change is critical in nature. The 900 rpm pump speed (1800 rpm engine speed) increase in fuel delivery is consistent with the post test powercurve data, which showed an increase in engine power/torque centering around the peak torque speed of the engine. Interestingly the 1700 rpm pump speed (3400 rpm engine speed) corresponding to the engines rated power point showed a decrease in fuel delivery. This is counter to what was observed during the post test powercurves where were noted an increase in BSFC observed while maintaining consistent power with pre-test measurements, which demonstrated an increase in overall fuel consumption of the engine.

Table 17 shows the pre and post test fuel injector calibration data. Some decrease in opening pressure was observed across the test duration. This trend is typical with this style injector, and does not appear to be excessive in nature. No issues were observed with tip leakage, chatter, or spray pattern when inspected, suggesting that the 25% ATJ had little impact on the injector operation over the 210hr test duration.

Table 16. GEP 6.5L(T) 25% ATJ Fuel Injection Pump Calibration

Stanadyne Pump Calibration / Evaluation

Pump Type : DB2831-6282 (arctic)	**SN: 17139503**
Test condition : 25% ATJ, Ambient Conditions	

PUMP RPM	Description	Spec.	Before	After	Change
1000	Transfer pump psi.	60-62 psi	61	65	4
	Return Fuel	225-375 cc	300	340	40
350	Low Idle	12-16 cc	12	16	4
	Housing psi.	8-12 psi	10	8	2
	Advance	3.5 deg. min	5	5	0
	Cold Advance Solenoid	0-1 psi.	6.9	0	6.9
750	Shut-Off	4 cc max.	0	0	0
900	Fuel Delivery	64.5-67.5 cc	67	70	3
1600	WOT Fuel delivery	58.5 min.	64	60	4
	WOT Advance	2.5 - 3.5 deg.	3.25	3.5	0.25
	Face Cam Fuel delivery	21.5 - 23.5	22	22	0
	Face Cam Advance	5.25 - 7.25 deg.	6.7	7	0.3
	Low Idle	11 - 12 deg.	11.2	11	0.2
1700	WOT Fuel Delivery	58 min.	64	60	4
1850	Fuel Delivery	33 cc min.	36	36	0
1975	High Idle	15 cc max.	2	2	0
	Transfer pump psi.	125 psi max.	103	105	2
200	WOT Fuel Delivery	58 cc min.	59	61	2
	WOT Shut-Off	4 cc max.	0	0	0
75	Low Idle Fuel Delivery	37 cc min.	45	60	15
	Transfer pump psi.	16 psi min.	25	25	0
	Housing psi.	0 -12 psi	8	6	2
	Air Timing	-.5 deg.(+/-.5 deg)	-0.5	-0.5	
	Fluid Temp. Deg. C		45	45	
	Date		12/1/2015	1/11/2016	

Notes :

Table 17. GEP 6.5L(T) 25% ATJ Fuel Injector Calibration Data

Test Number	Injection Pump ID	Test Fuel	Injector ID	Opening Pressure		Tip Leakage		Chatter		Spray Pattern		Inspection Date	
				Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
AF9367-65T1-W-210	DB2-6282 SN17139503	AF9367 25% ATJ Blend	1	2100	1800	pass	pass	pass	pass	pass	pass	150603	160110
			2	2125	1950	pass	pass	pass	pass	pass	pass		
			3	2125	1875	pass	pass	pass	pass	pass	pass		
			4	2100	1825	pass	pass	pass	pass	pass	pass		
			5	2125	1825	pass	pass	pass	pass	pass	pass		
			6	2100	1875	pass	pass	pass	pass	pass	pass		
			7	2175	1875	pass	pass	pass	pass	pass	pass		
			8	2150	1925	pass	pass	pass	pass	pass	pass		
Pre & Post-Test Inspection Completed by REG													

7.3.3 Pre & Post Test Photo Documentation

Photographs were captured of the piston crowns, cylinder head, and injector tips before and after testing to document changes in condition and deposits. Each of these are presented in the following sections.

Injector Tips

Figure 29 through Figure 36 presents the GEP 6.5L(T) 25% ATJ injector tip condition for all cylinders before and after testing. Deposition levels appear consistent between all eight injectors, and overall typical of used functioning injectors. These photos, coupled with the pre and post test injector calibration checks, suggest that the 25% ATJ blend does not have significant impact on expected injector operation/performance. No baseline JP8 or ULSD photos exist to compare to.

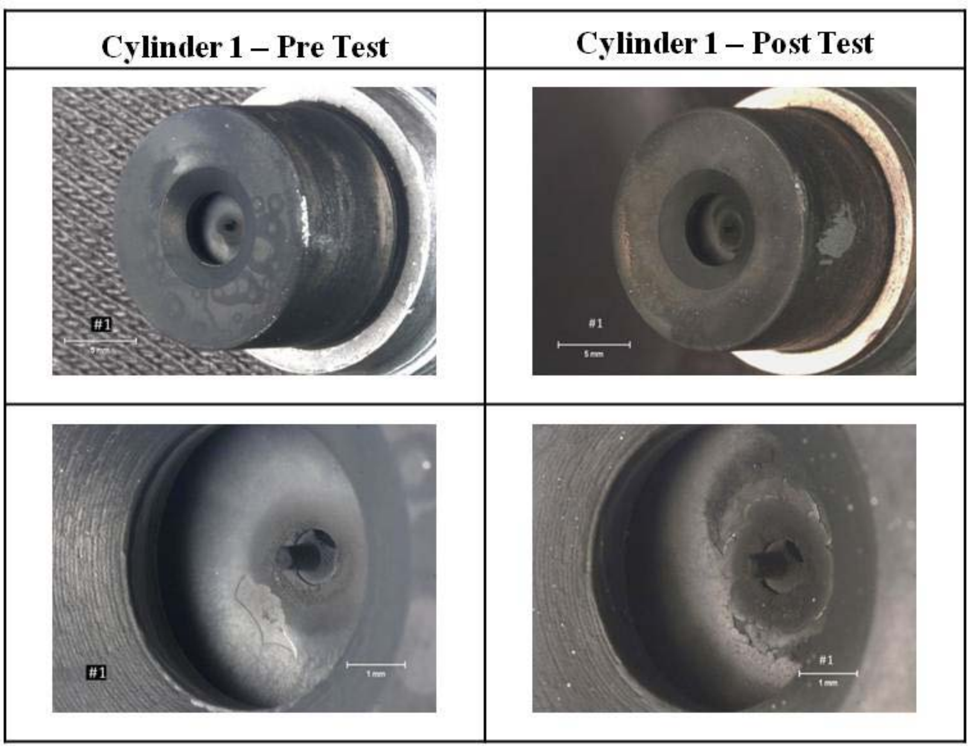

Figure 29. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 1

Cylinder 2 – Pre Test	Cylinder 2 – Post Test

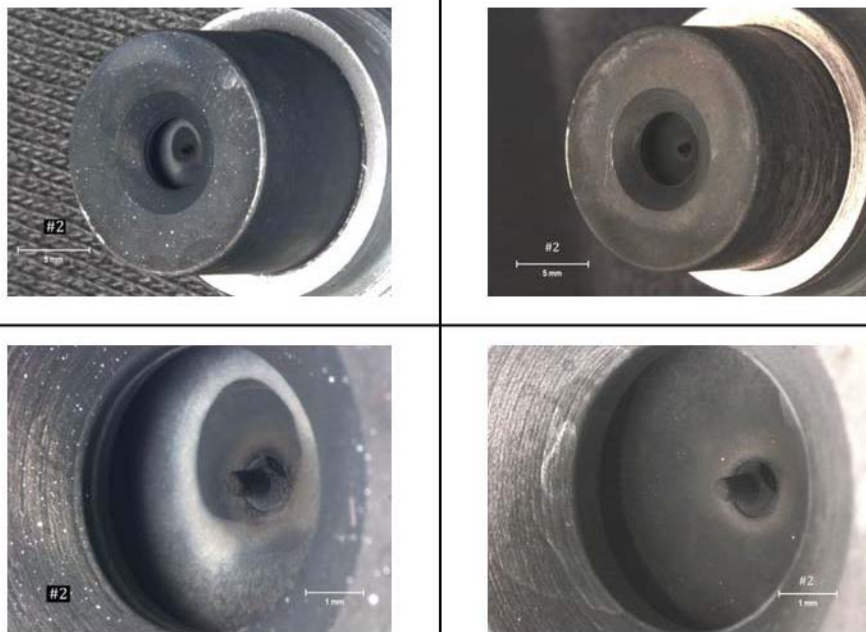

Figure 30. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 2

Cylinder 3 – Pre Test	Cylinder 3 – Post Test

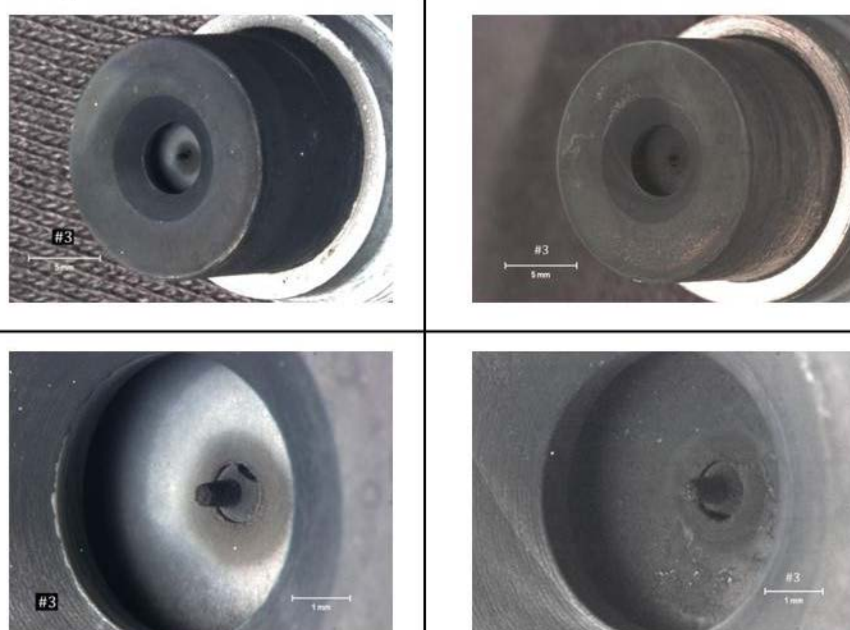

Figure 31. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 3

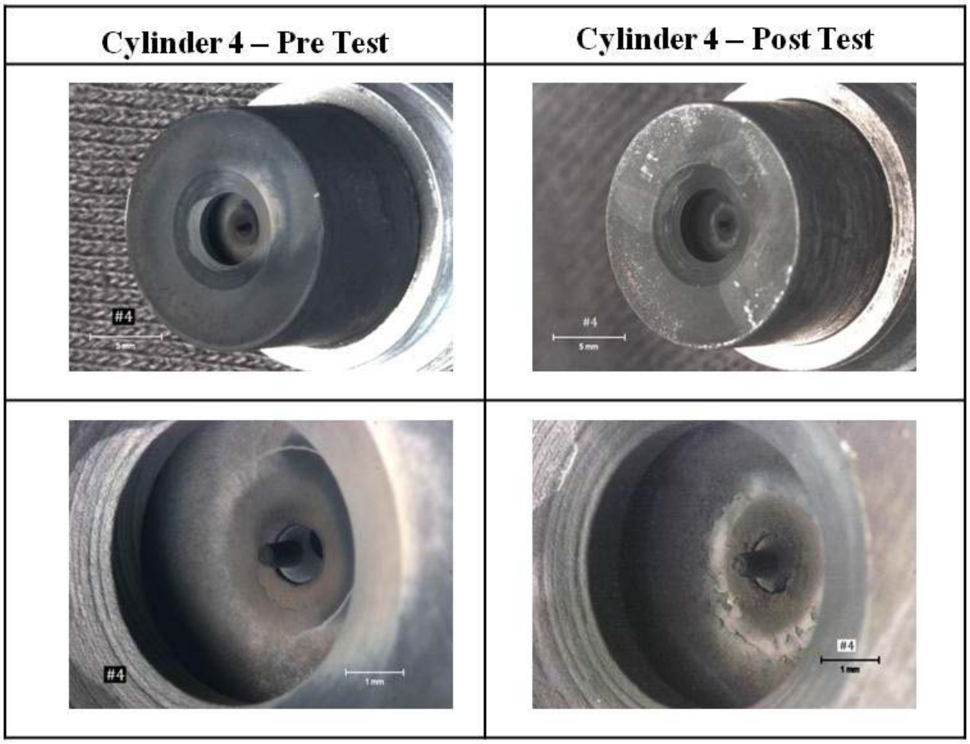

Figure 32. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 4

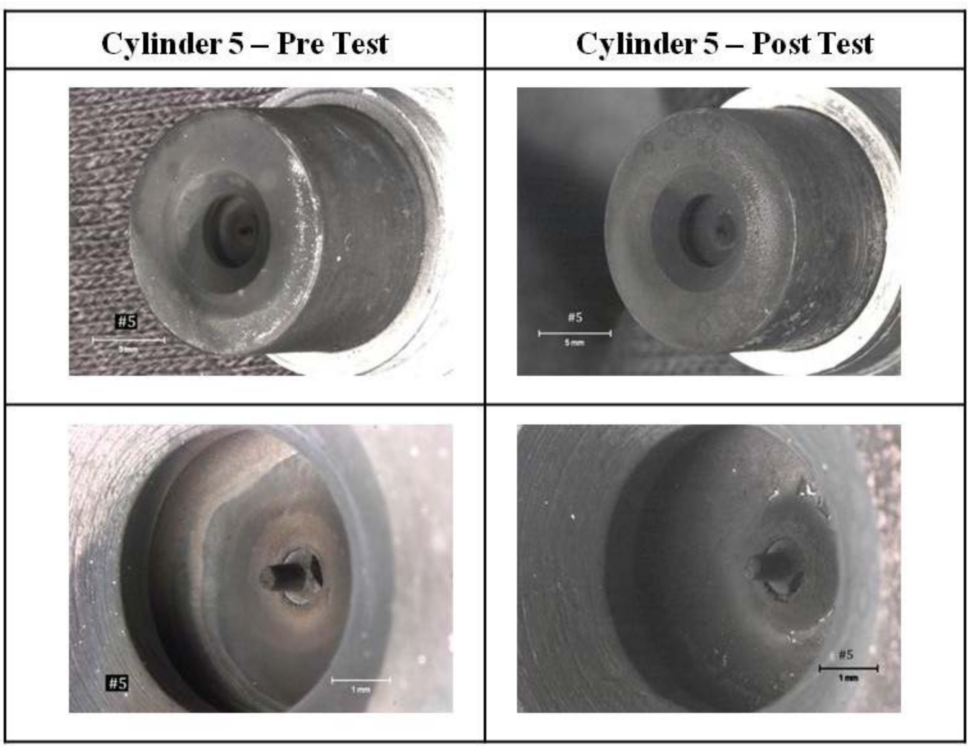

Figure 33. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 5

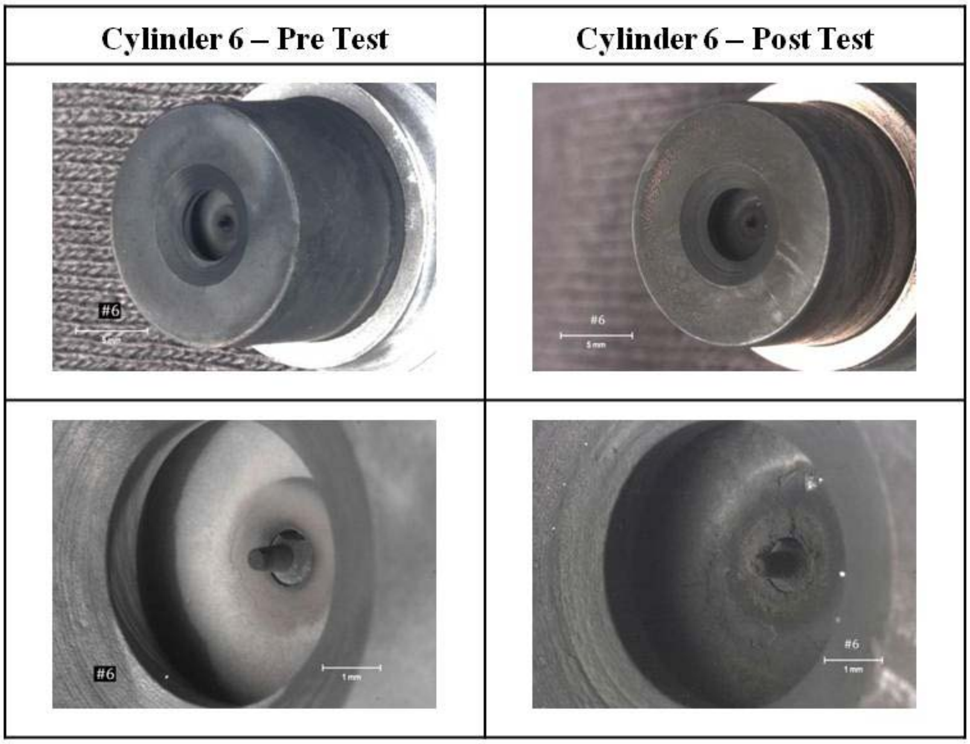

Figure 34. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 6

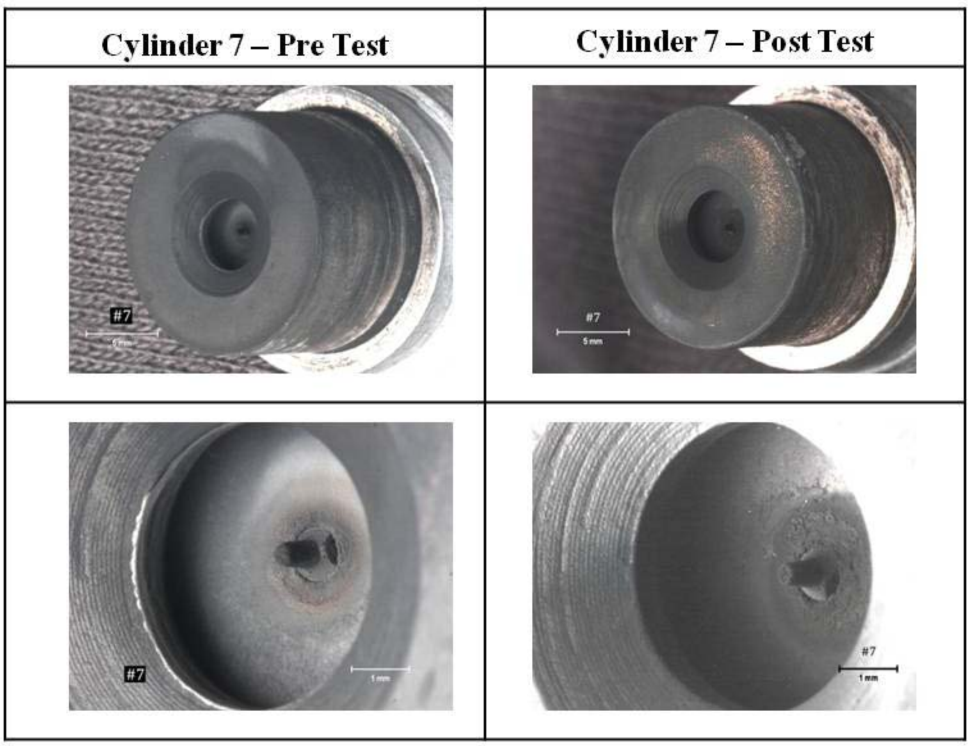

Figure 35. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 7

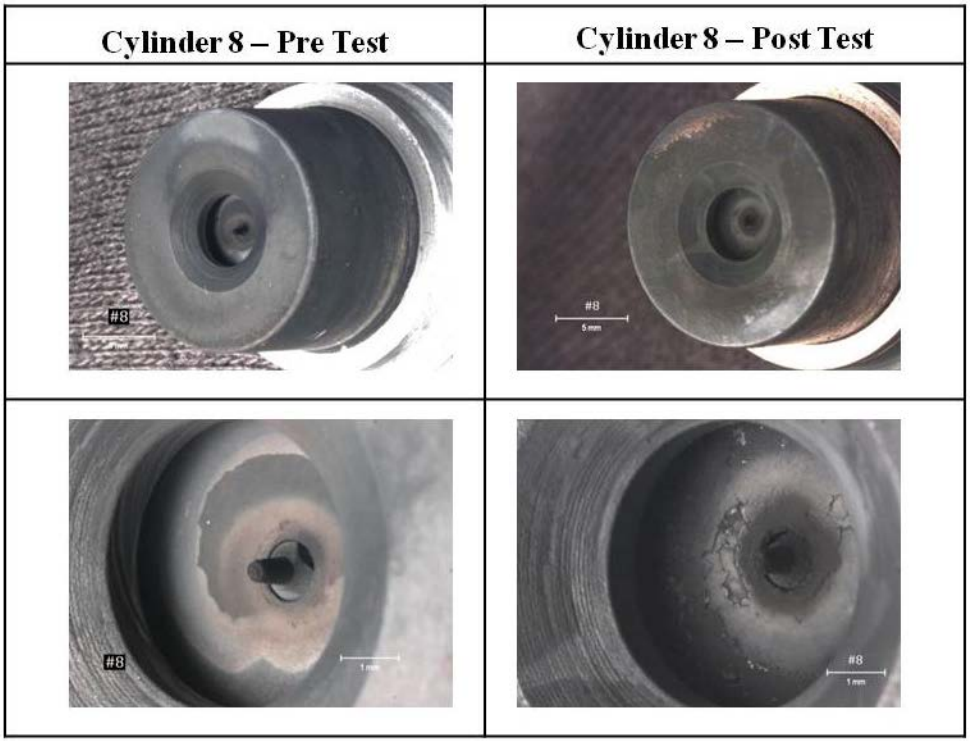

Figure 36. GEP 6.5L(T) 25% ATJ Injector Photos – Cylinder 8

<u>Piston Crown and Cylinder Head Fire Deck</u>

Figure 37 and Figure 38 show the pre and post test photos of the piston crowns for the GEP 6.5L(T) 25% ATJ evaluation. Overall deposition levels are consistent across all pistons, and appear to be typical in nature. No baseline JP8 or ULSD photos exist to compare to.

Figure 39 and Figure 40 show the pre and post test cylinder head fire deck photos. The heavy orange discoloration for location #1 and #7 is attributed to flash oxidation after being exposed to small volumes of engine coolant released upon engine disassembly. Remaining deposits are consistent across all cylinders, and appear to be typical in nature. No baseline JP8 or ULSD photos exist to compare to.

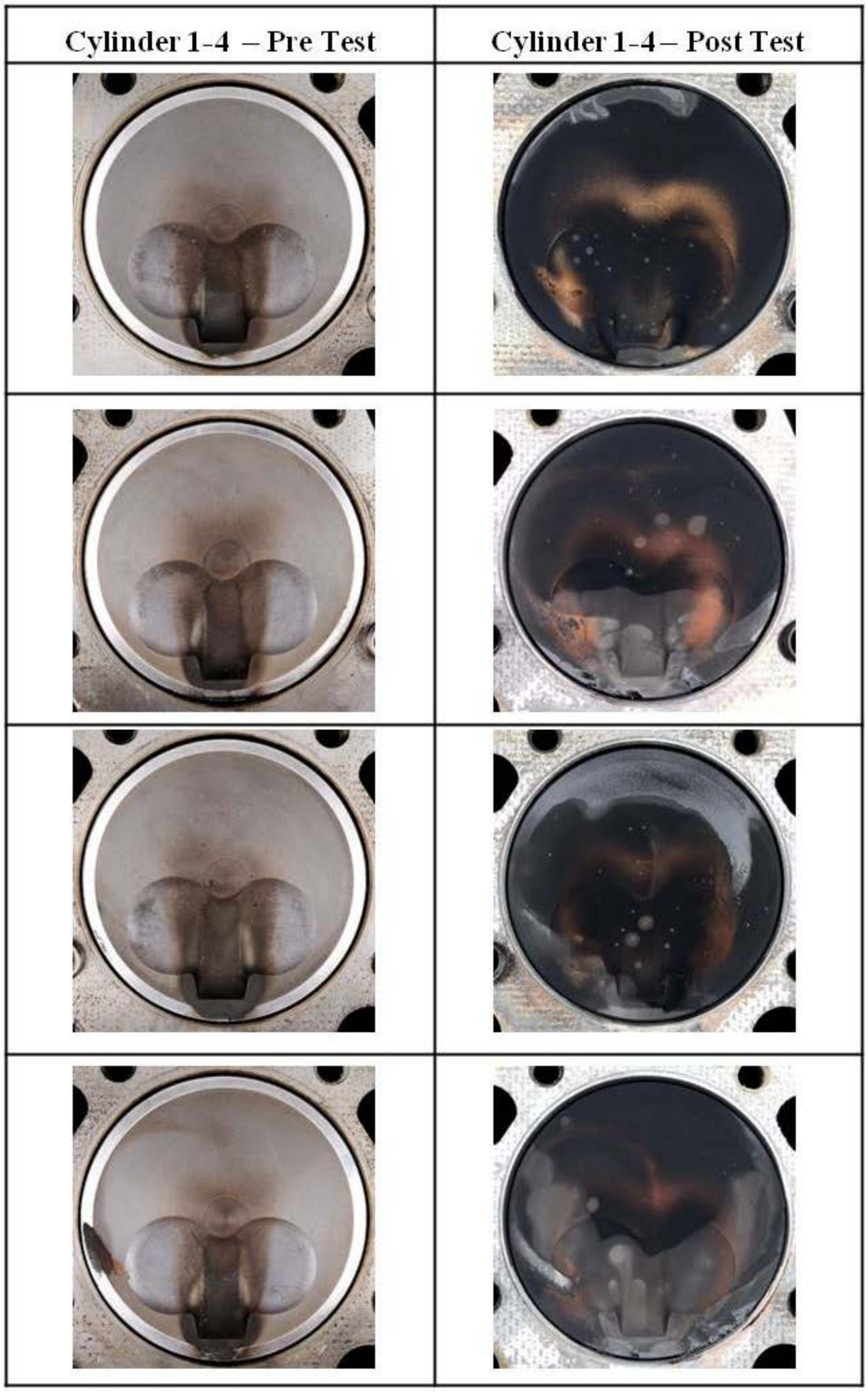

Figure 37. GEP 6.5L(T) 25% ATJ – Pre & Post Test #1-4 Piston Crowns

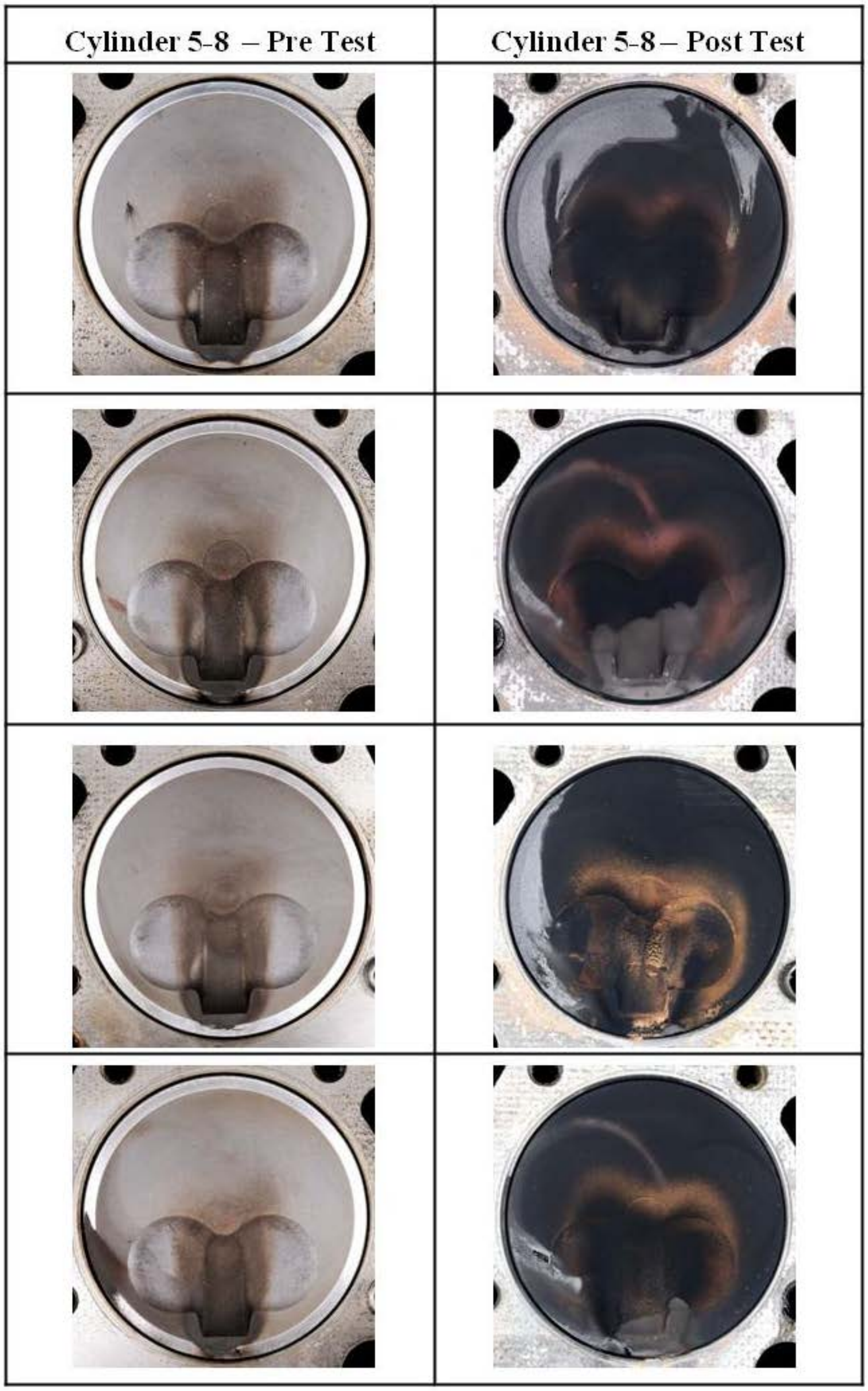

Figure 38. GEP 6.5L(T) 25% ATJ – Pre & Post Test #5-8 Piston Crowns

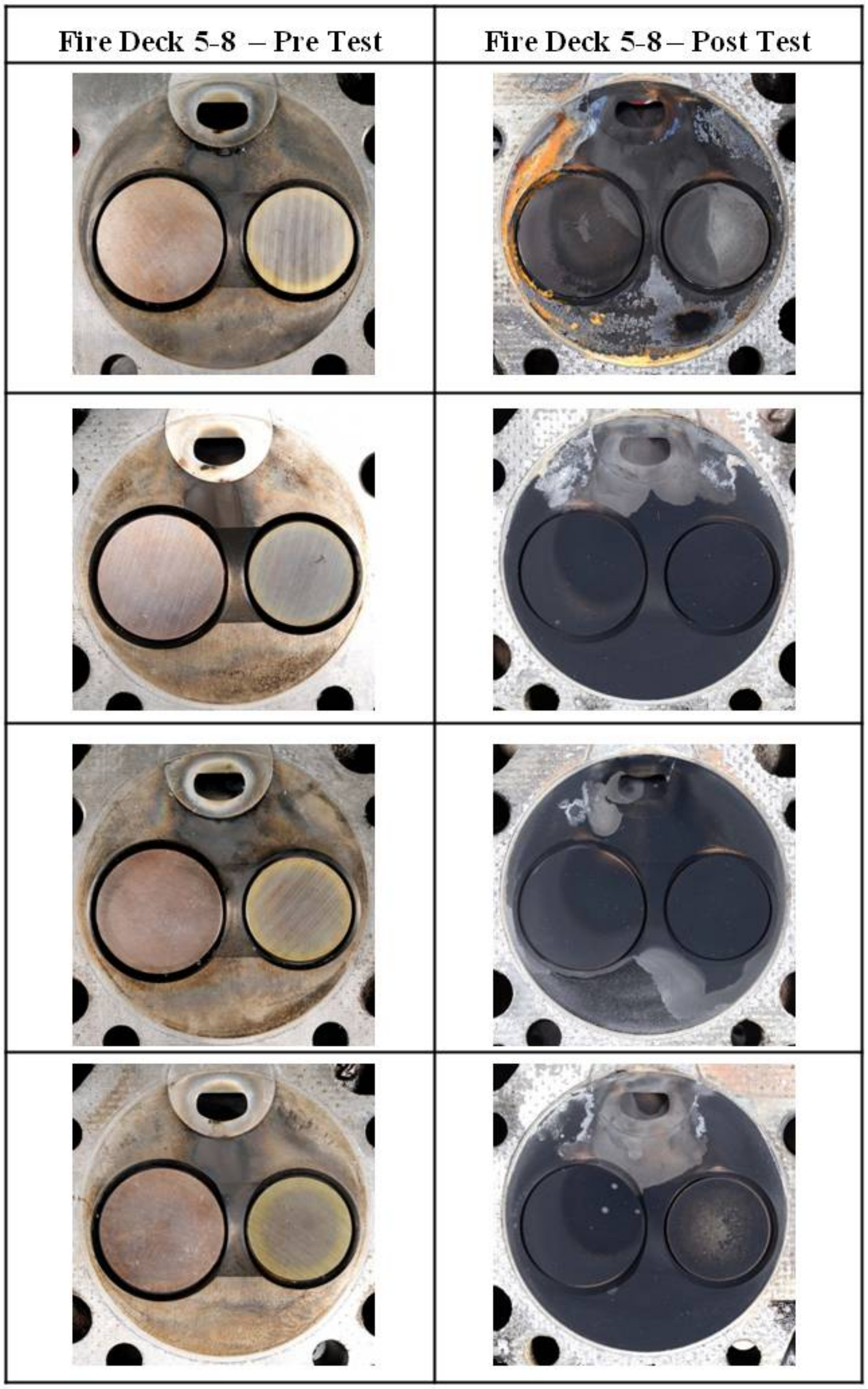

Figure 39. GEP 6.5L(T) 25% ATJ Pre & Post Test #1-4 Fire Deck

Fire Deck 5-8 – Pre Test	Fire Deck 5-8 – Post Test
	
	
	
	

Figure 40. GEP 6.5L(T) 25% ATJ Pre & Post Test #5-8 Fire Deck

8.0 CONCLUSIONS

With the technical issues presented in this report related to the CAT C7 evaluation and the DOC GEP 6.5L(T) evaluations, a full analysis of the compatibility of the 25% ATJ blend is not possible. The remainder of the discussion will focus on information that can be summarized from the testing completed.

For the C7 engine, all pre test powercurves and fuel maps at both ambient and DOC suggests that the C7 engine is compatible with the 25% ATJ regarding overall engine performance. No unusual operating conditions were noted, and overall engine output achieved expected levels based on fuel and temperature conditions. Without the complete 210hr duration test data, long term compatibility of the C7 engine with the 25% ATJ blend cannot be assessed. The technical issues experienced during the C7 durability test were successfully ruled non-fuel related.

For the GEP 6.5L(T) engine, overall testing showed good compatibility with the 25% ATJ fuel blend at ambient conditions. Since DOC powercurves were unable to be completed, a full assessment of the engines response using the 25% ATJ is not possible, but the Stanadyne pump used by this engine is historically sensitive to high fuel temperatures regardless of fuel type. It would be expected that operation at DOC would demonstrate a marked reduction in engine output power, and reduced durability of the injection if operated at length at DOC. However testing conducted at ambient condition showed good overall compatibility, and pre and post test powercurves demonstrated no significant change in power output across the 210hr test duration. Post test powercurves did show an increase in measured BSFC (i.e., fuel consumption normalized against engine power), which does suggest some amount of wear in the injection system. Despite this, observed changes were considered typical for this style injection system under the duty cycle completed. Pre and post test fuel system calibration data suggests that the minimum treat rate of the 25% ATJ was providing adequate protection of the fuel wetted components at these lower operating temperatures.

The peak pre-chamber pressures are determined by fuelling, energy content, and ignition quality, thus ULSD exhibited higher peak pressures than the ATJ runs because more fuel is injected. Because the ATJ pressures were lower than ULSD, engine durability should not be impacted with ATJ.

The locations of peak pressure with the ATJ blends and the location of the 50% Mass Fraction Burned were impacted by fuel injection timing retard due to fuel bulk modulus. The impact of combustion retard is lower engine efficiency with ATJ. Injector needle lift traces show injection retard with ATJ blend, with the ATJ runs after the durability test slightly retarded further.

The pressure rise rates are affected by the amount of fuel in the cylinder at ignition. Due to the equivalent or lower pressure rise rates, the ATJ blend should not impact engine durability.

The peak heat release rates can affect heat transfer. Across the speed range the DF2-Pre run had the most consistent peak heat release rates but the ATJ runs were not significantly different.

The 10-90% Mass Fraction Burn duration would be linked to the injected fuel quantity and fuel volatility. A less volatile fuel such as ULSD should exhibit more diffusion controlled combustion, extending the burn duration. The ATJ blend has a shorter burn duration than ULSD.

The general effect of the durability test on ATJ combustion at full load is a slight start of combustion retard, a longer burn duration, lower peak pressures, and lower peak rate of pressure rise across the full load power curve speed range. Overall the use of an ATJ blend in the durability test did not alter the combustion of the GEP6.5LT engine such that engine durability would impacted.

9.0 REFERENCES

1. Yost, Douglas M., Frame, Edwin A., *"GEP 6.5L Engine Cetane Window Evaluation for ATJ/JP-8 Fuel Blends,"* Interim Report TFLRF No. 470, September 2015

2. Brandt, Adam C., Frame, Edwin A., *"Evaluation of 25-Percent ATJ Fuel Blends in the John Deere 4045HF280 Engine,"* Interim Report TFLRF No. 458, August 2014

3. Hansen, Gregory A., Yost, Douglas M., Frame, Edwin A., *"Tactical/Combat Engines Cetane Window Evaluation,"* Interim Report TFLRF No. 426, January 2013

4. Development of Military Fuel/Lubricant/Engine Compatibility Test, CRC Report 406, January 1967

5. Yost, Douglas M., Frame, Edwin A., *"Fuel Maps for the GEP 6.5LT Engine When Operating on ATJ/JP-8 Fuel Blends at Ambient and Elevated Temperatures,"* Interim Report TFLRF No. 464, August 2015

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APPENDIX A.

GEP 6.5LT FULL LOAD POWER CURVE COMBUSTION DIAGRAMS

The following combustion indicator diagrams are for each of the 14 engine speeds utilized for the full load power curve. The peak torque speed (1800-RPM) and the peak power speed (3400-RPM) indicator diagrams were included in the discussions related to the full-load power curves. The plots in Figure A-1 through Figure A-42 include three plots for each of the 14-speeds. These three plots include the engine pre-chamber pressures, the Heat Release Rate with needle lift, and the Mass Fraction Burned curve for each of the DF2-Pre, ATJ-Pre, and ATJ-Post fuels and runs.

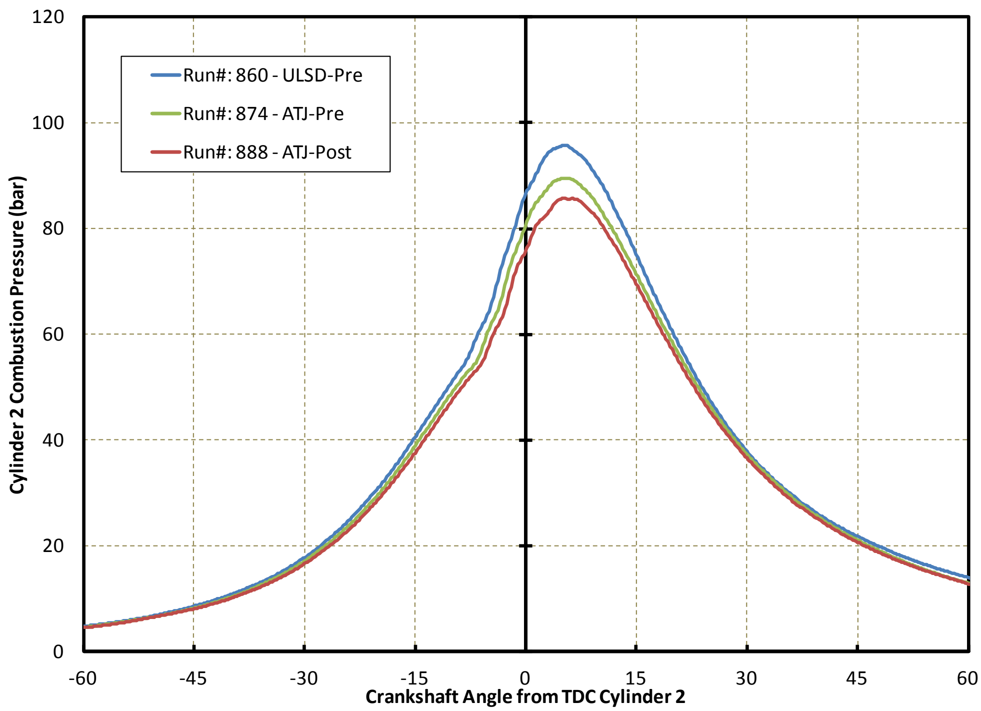

Figure A-1. Pre-Chamber Pressure Histories for 1000-RPM and 100% Load

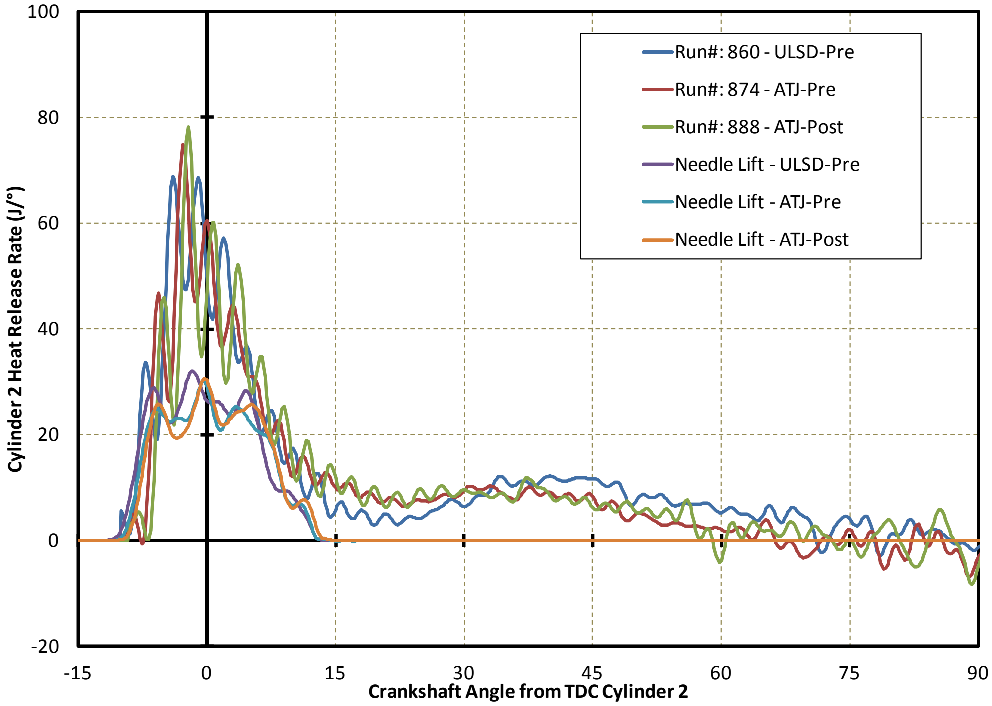

Figure A-2. Heat Release Rate Histories for 1000-RPM and 100% Load

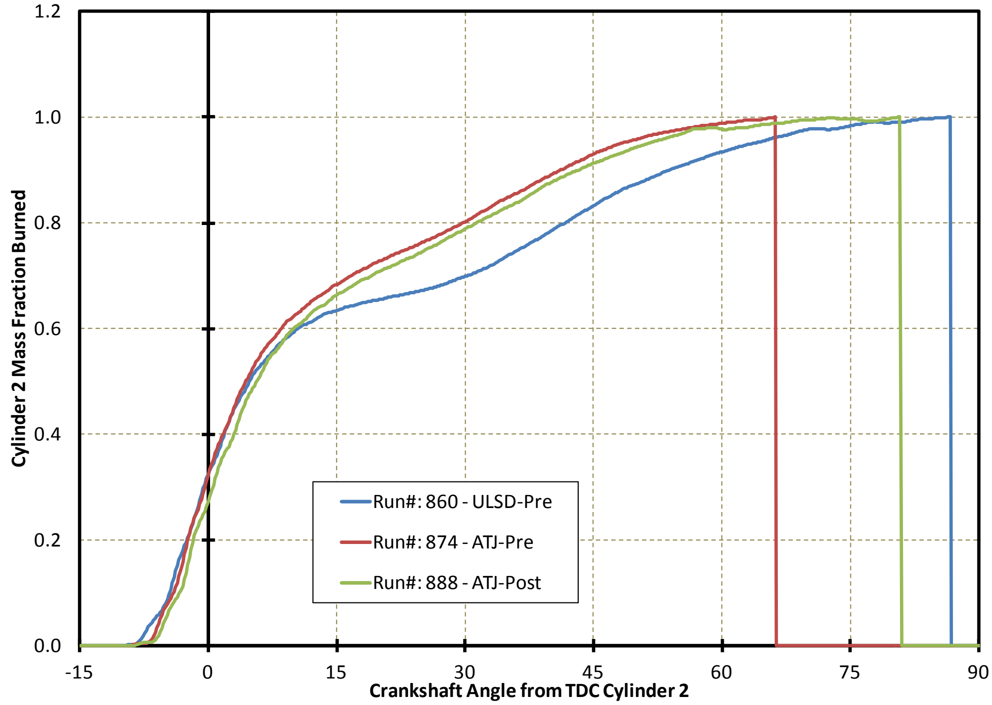

Figure A-3. Fuel Mass Fraction Burned for 1000-RPM and 100% Load

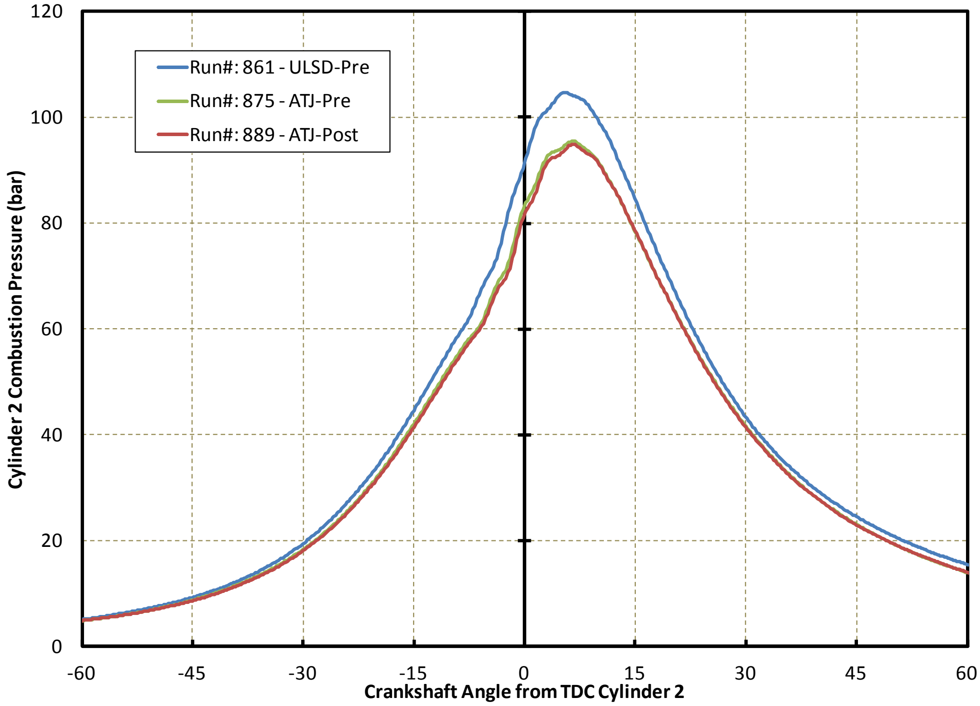

Figure A-4. Pre-Chamber Pressure Histories for 1200-RPM and 100% Load

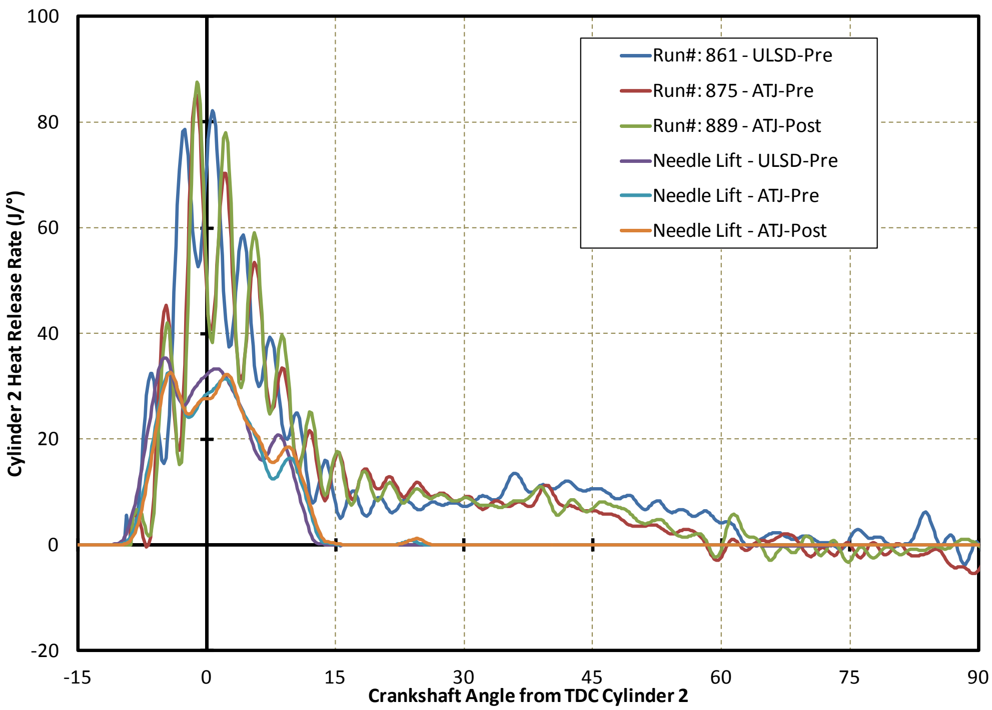

Figure A-5. Heat Release Rate Histories for 1200-RPM and 100% Load

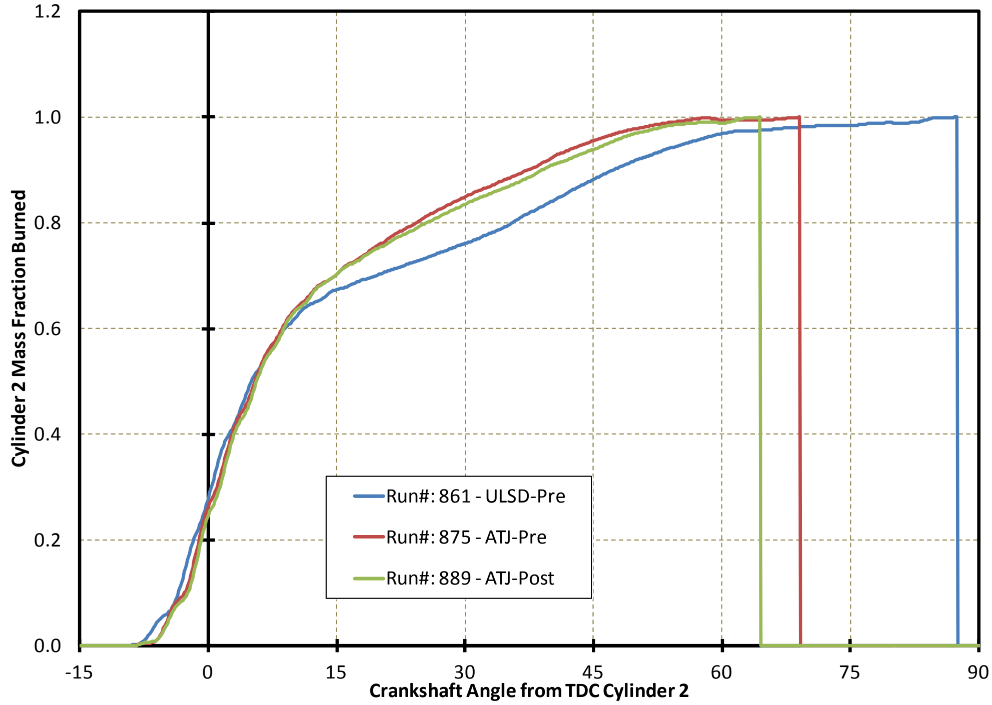

Figure A-6. Fuel Mass Fraction Burned for 1200-RPM and 100% Load

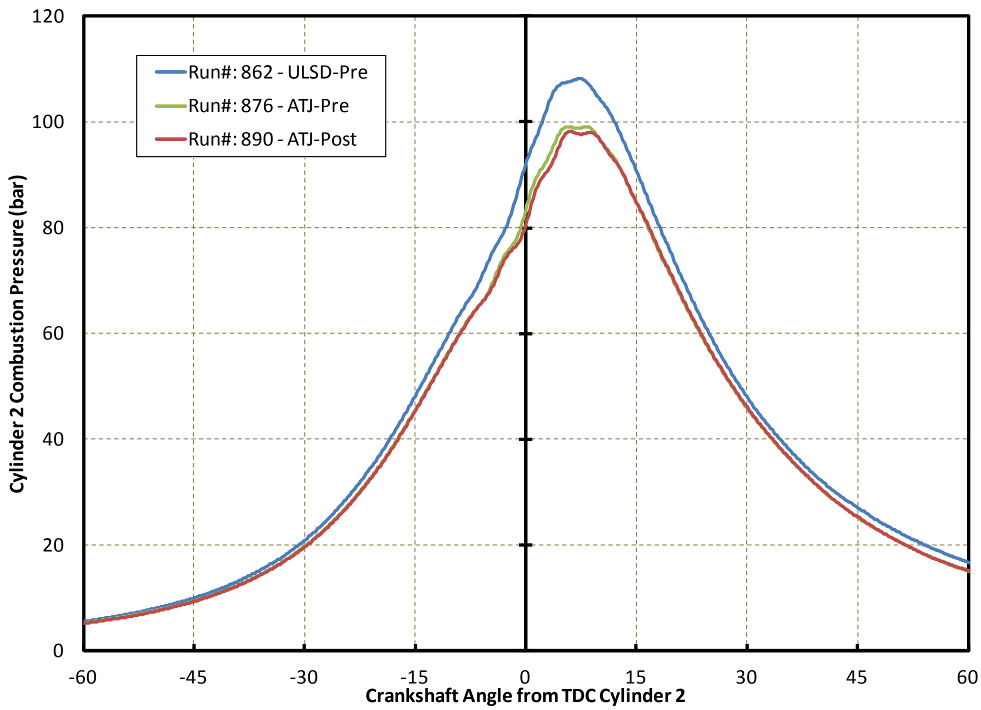

Figure A-7. Pre-Chamber Pressure Histories for 1400-RPM and 100% Load

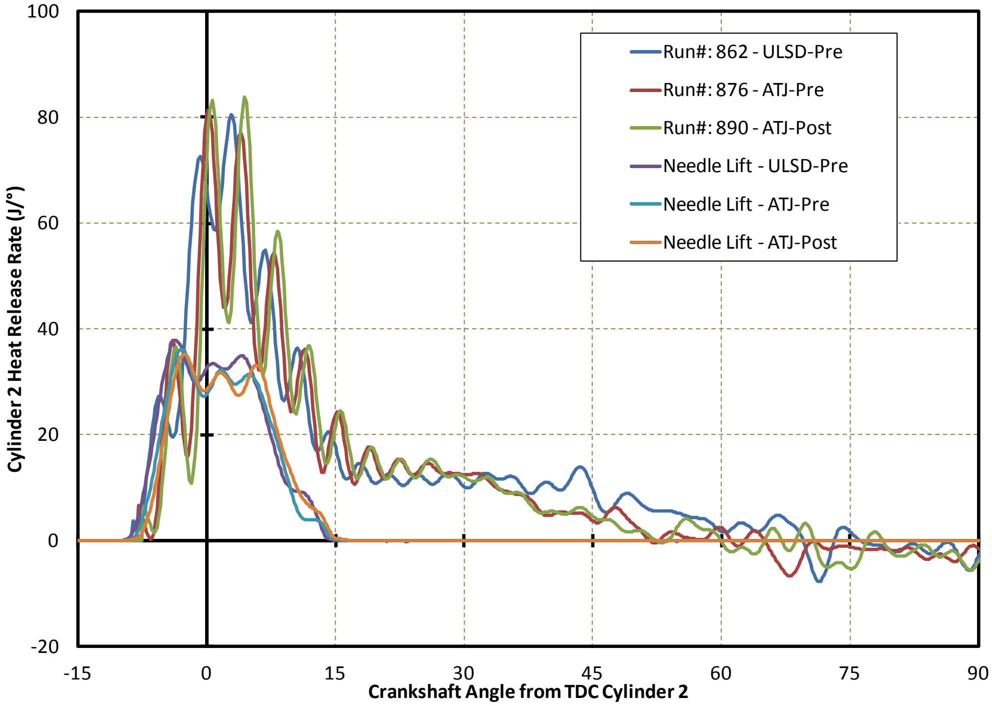

Figure A-8. Heat Release Rate Histories for 1400-RPM and 100% Load

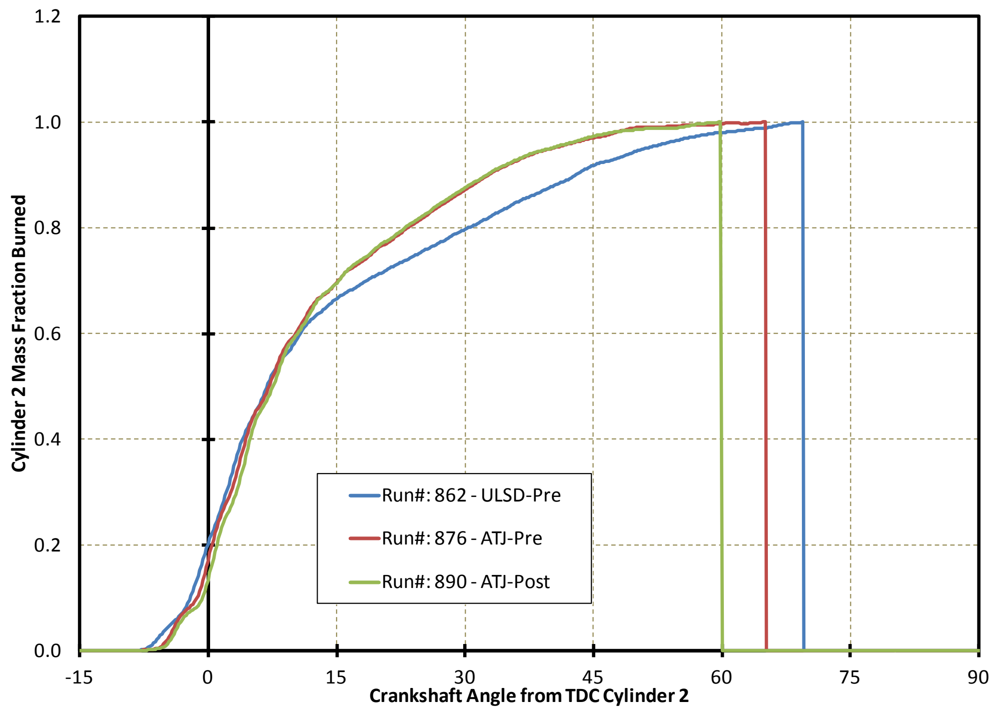

Figure A-9. Fuel Mass Fraction Burned for 1400-RPM and 100% Load

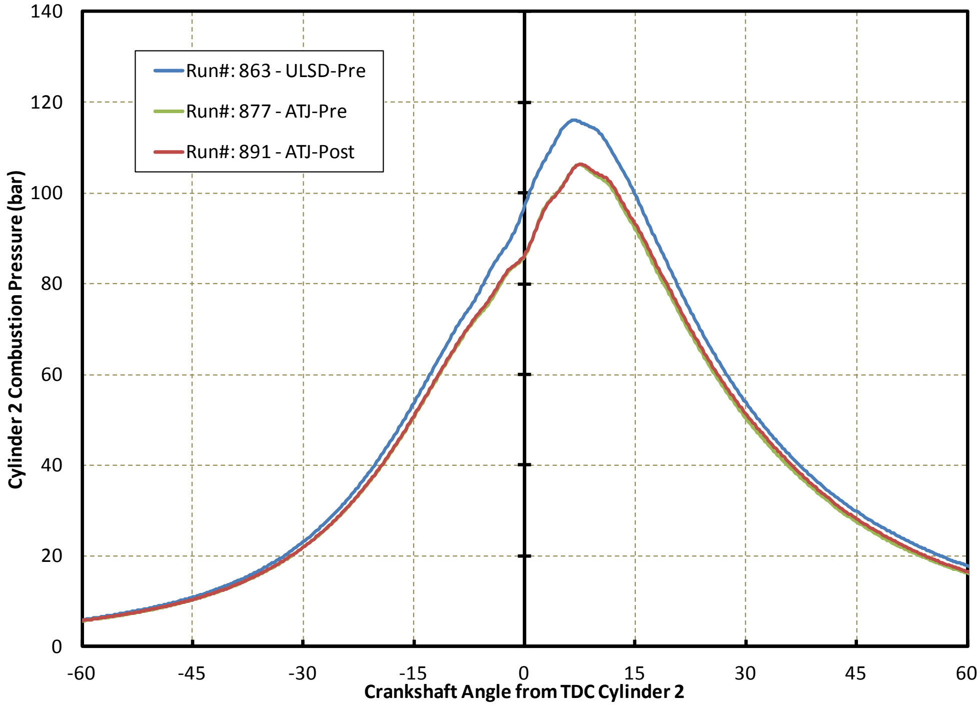

Figure A-10. Pre-Chamber Pressure Histories for 1600-RPM and 100% Load

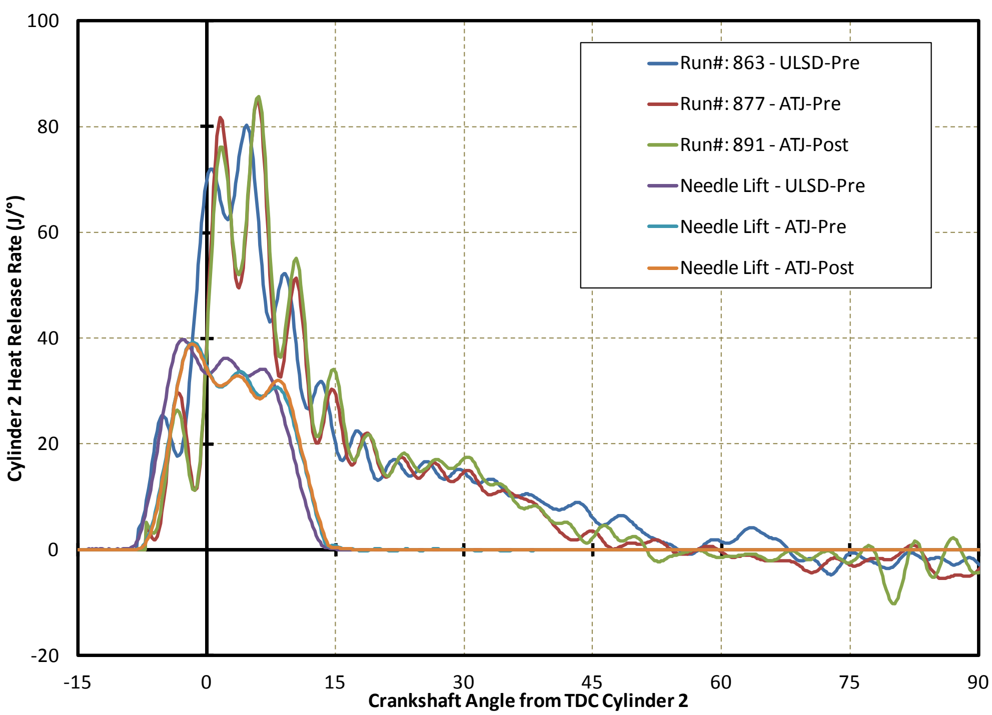

Figure A-11. Heat Release Rate Histories for 1600-RPM and 100% Load

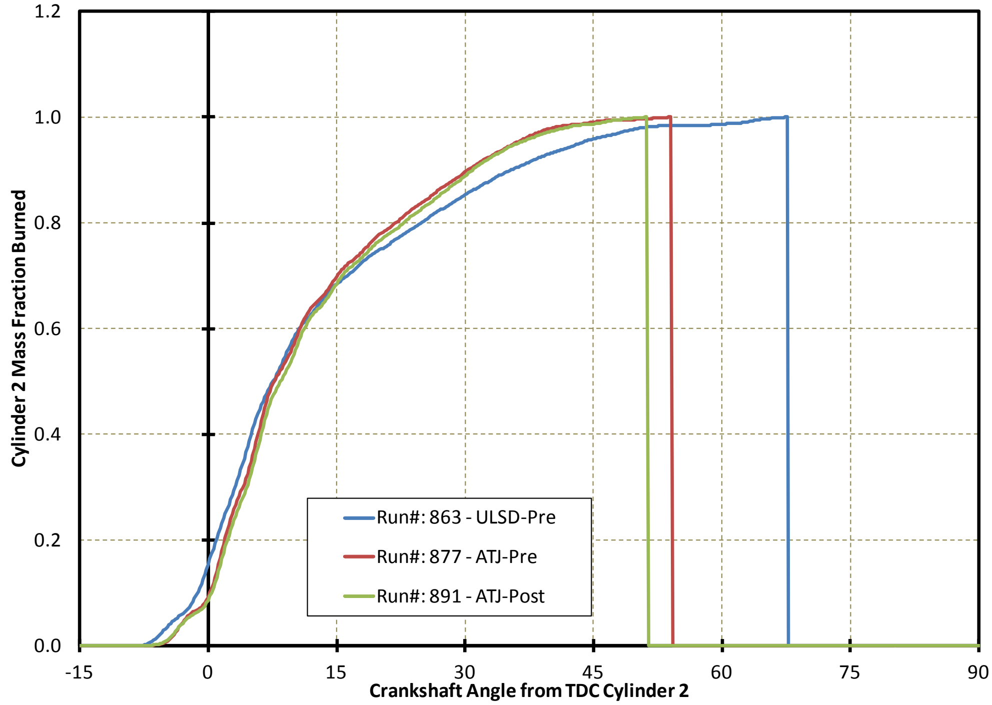

Figure A-12. Fuel Mass Fraction Burned for 1600-RPM and 100% Load

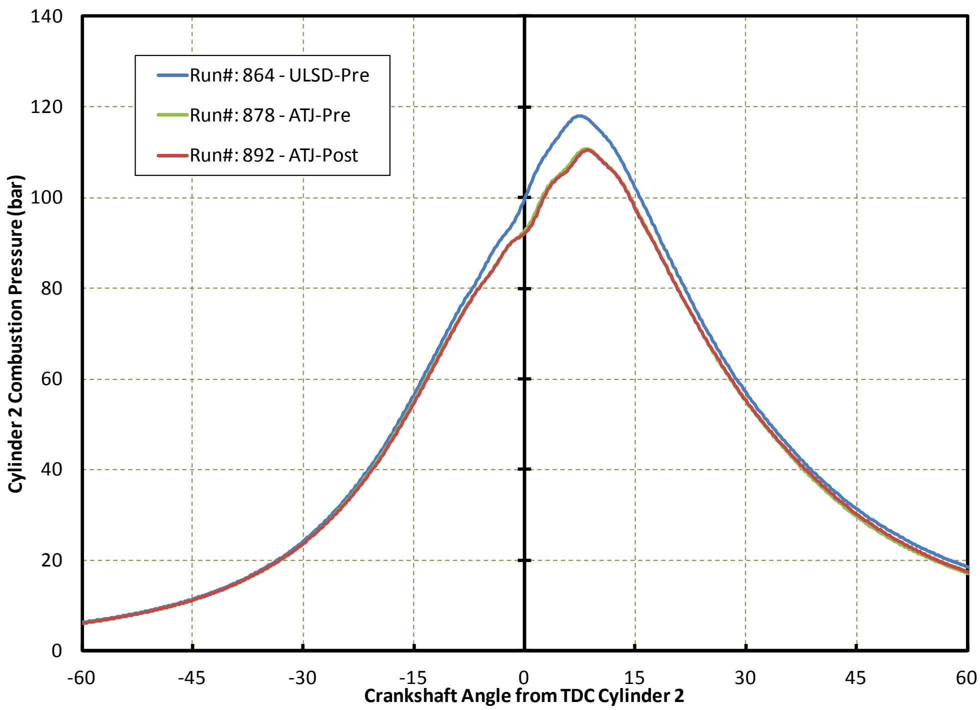

Figure A-13. Pre-Chamber Pressure Histories for 1800-RPM and 100% Load

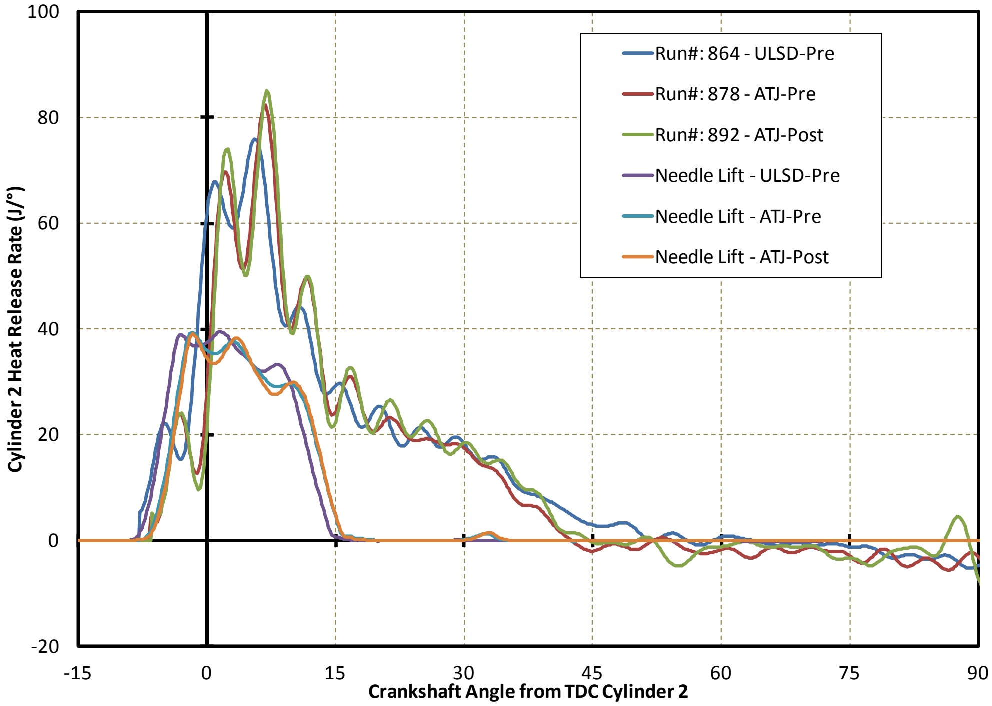

Figure A-14. Heat Release Rate Histories for 1800-RPM and 100% Load

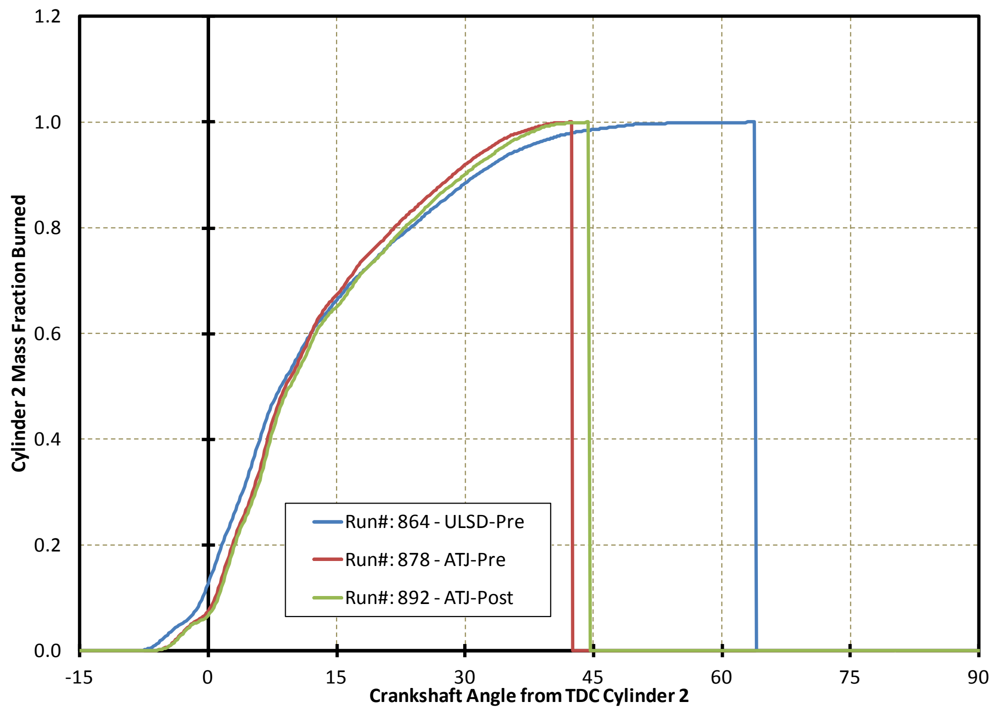

Figure A-15. Fuel Mass Fraction Burned for 1800-RPM and 100% Load

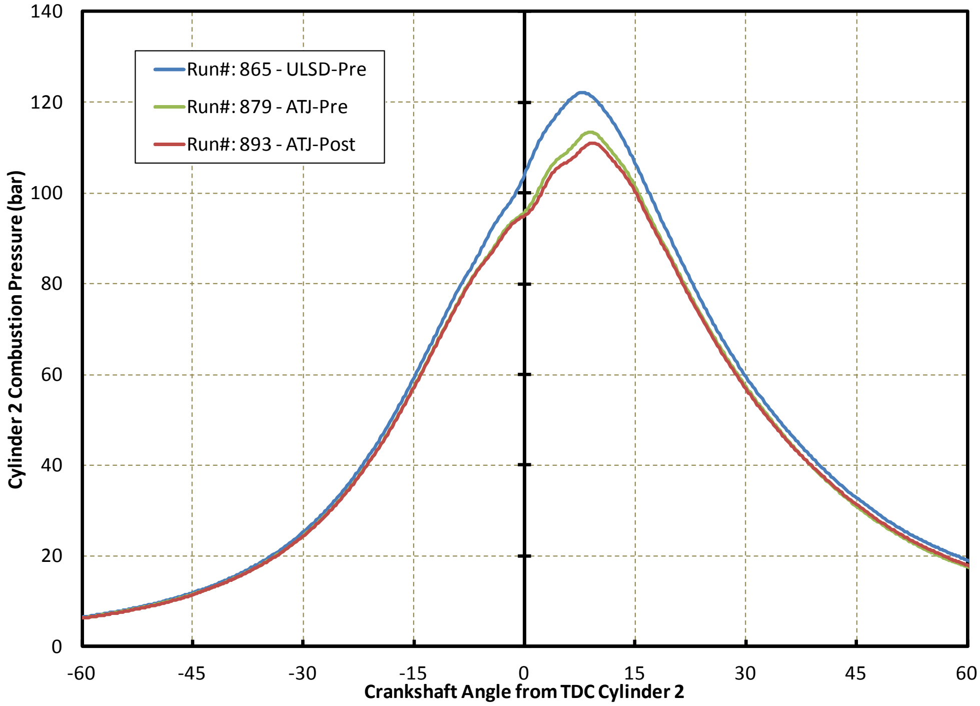

Figure A-16. Pre-Chamber Pressure Histories for 2000-RPM and 100% Load

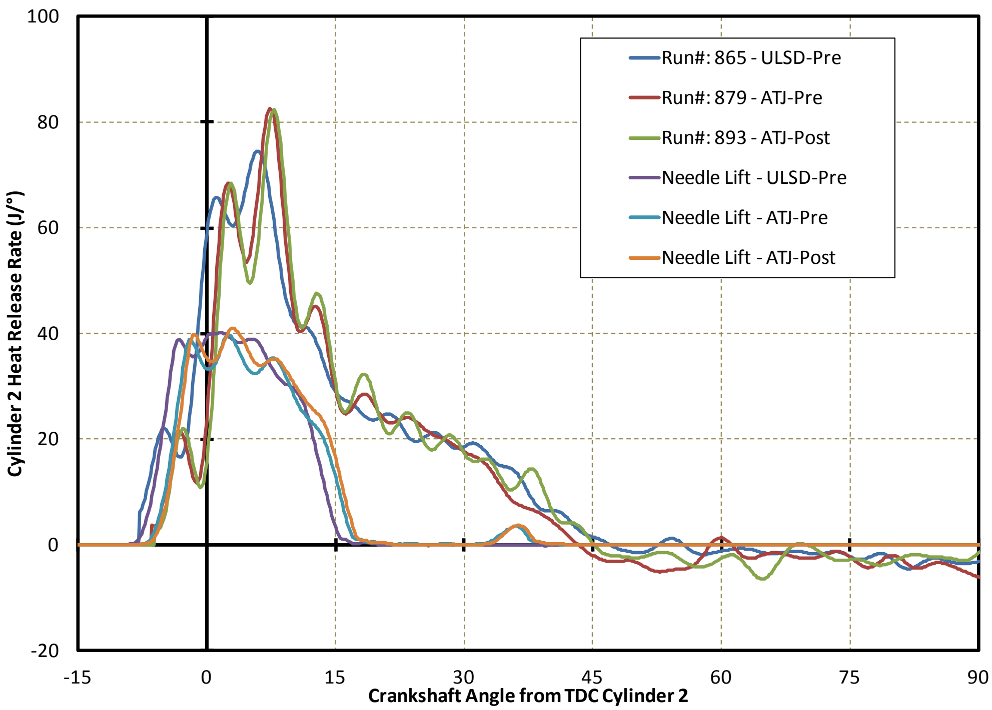

Figure A-17. Heat Release Rate Histories for 2000-RPM and 100% Load

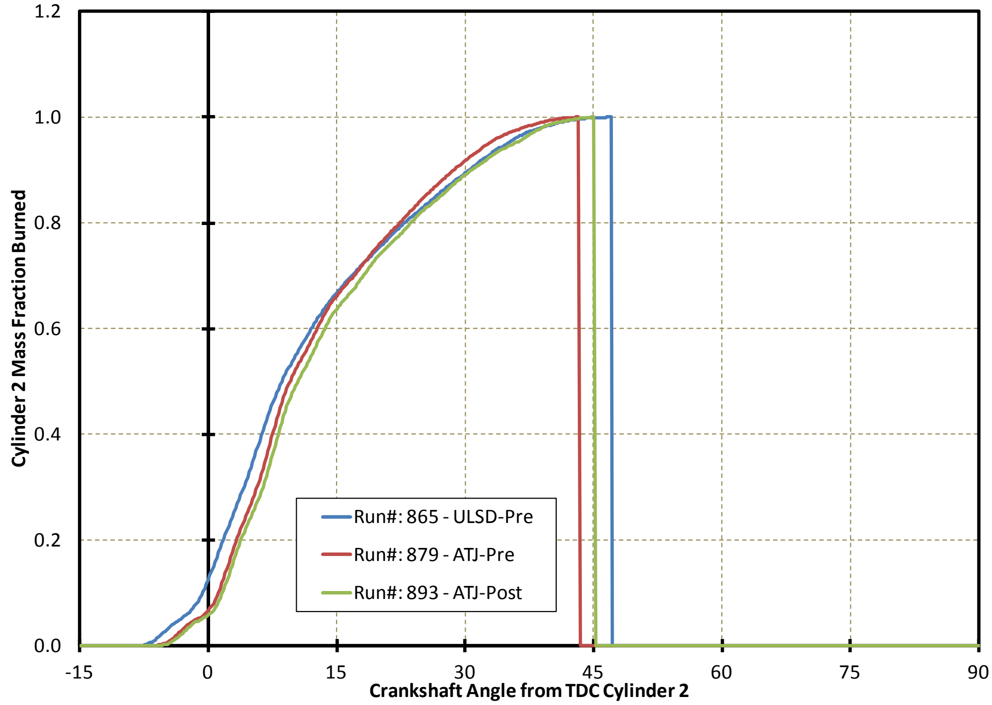

Figure A-18. Fuel Mass Fraction Burned for 2000-RPM and 100% Load

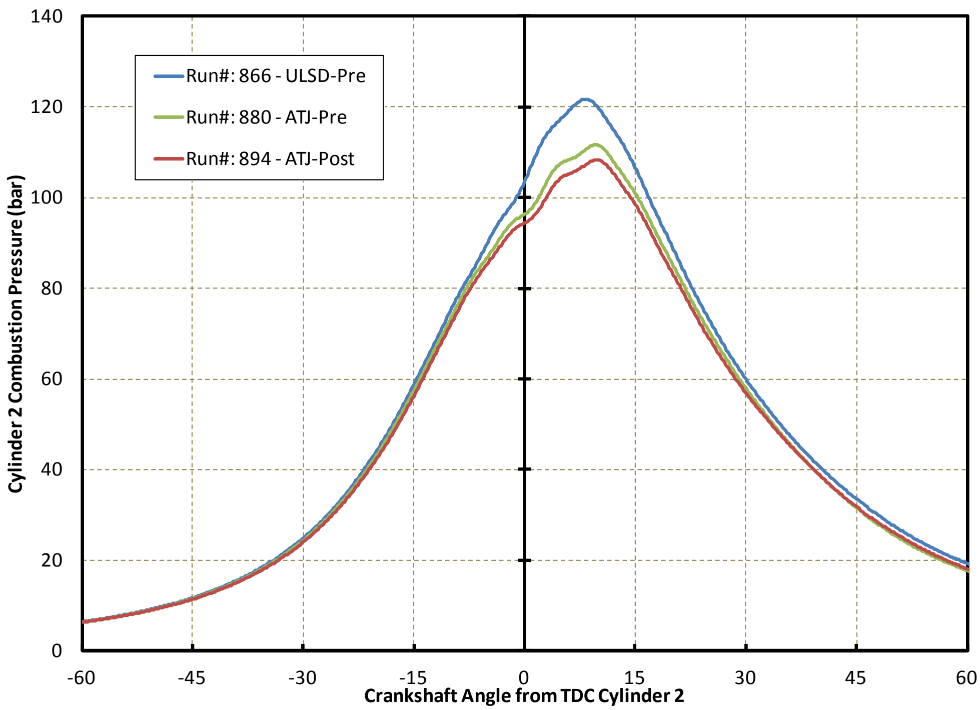

Figure A-19. Pre-Chamber Pressure Histories for 2200-RPM and 100% Load

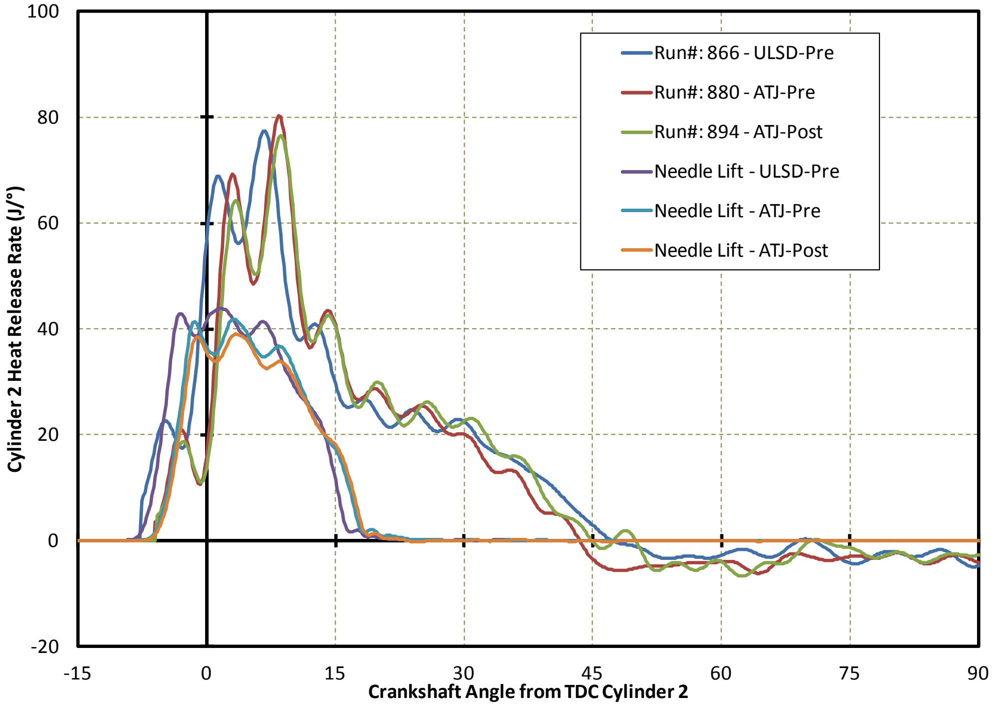

Figure A-20. Heat Release Rate Histories for 2200-RPM and 100% Load

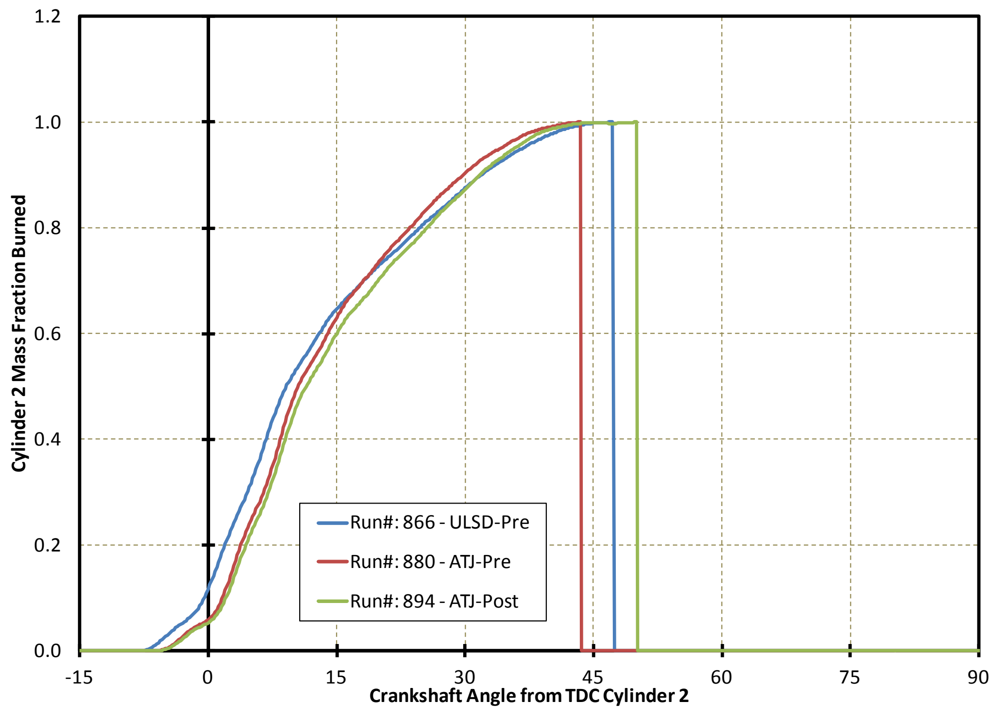

Figure A-21. Fuel Mass Fraction Burned for 2200-RPM and 100% Load

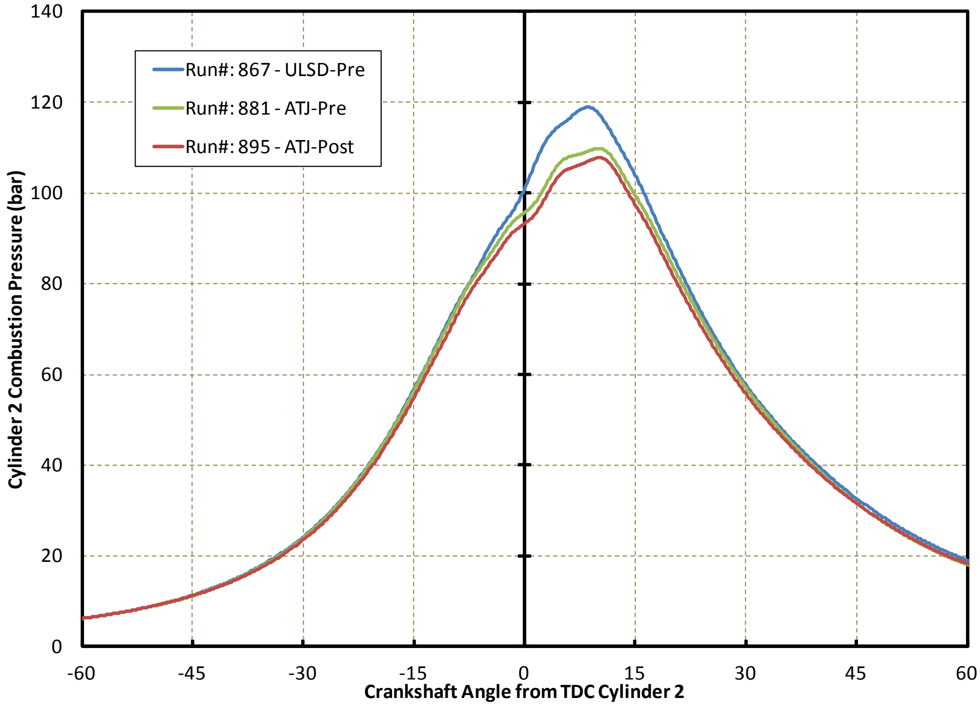

Figure A-22. Pre-Chamber Pressure Histories for 2400-RPM and 100% Load

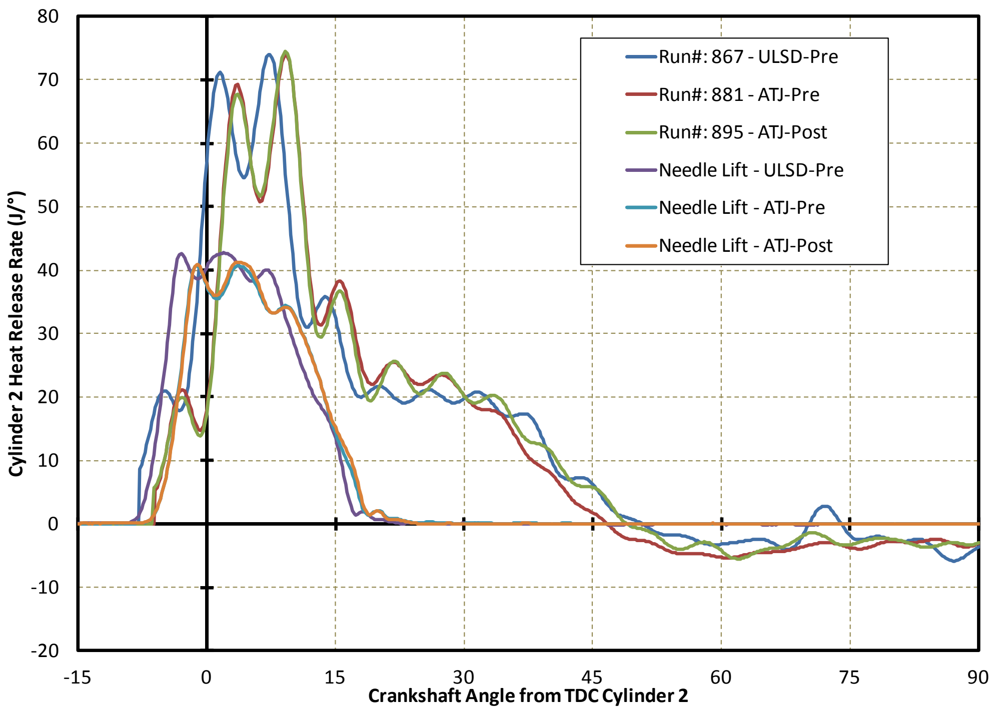

Figure A-23. Heat Release Rate Histories for 2400-RPM and 100% Load

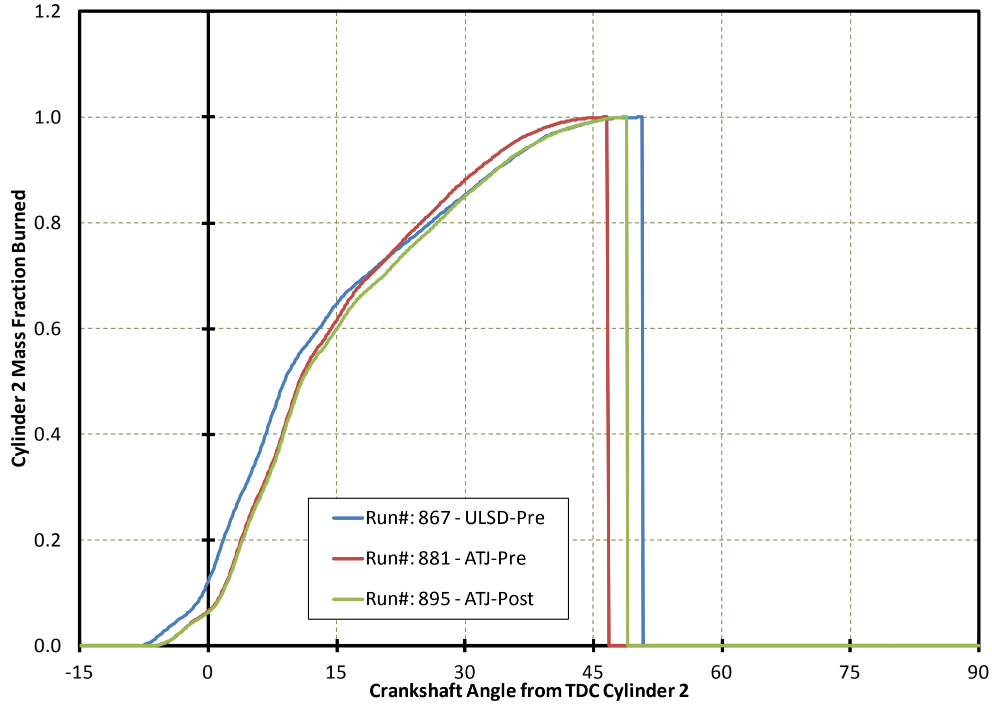

Figure A-24. Fuel Mass Fraction Burned for 2400-RPM and 100% Load

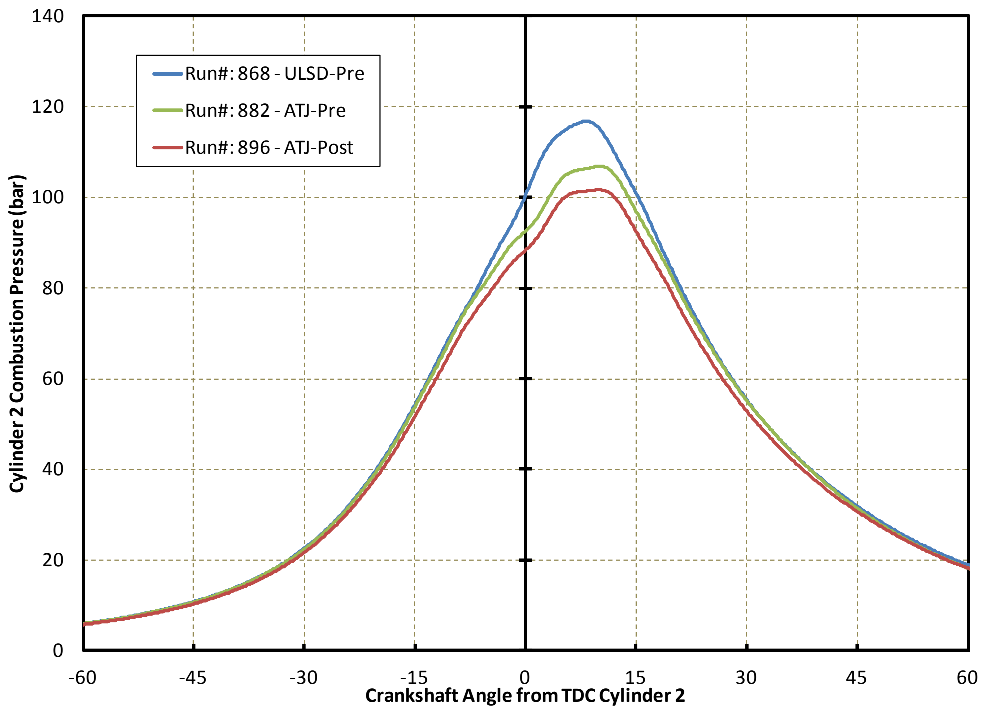

Figure A-25. Pre-Chamber Pressure Histories for 2600-RPM and 100% Load

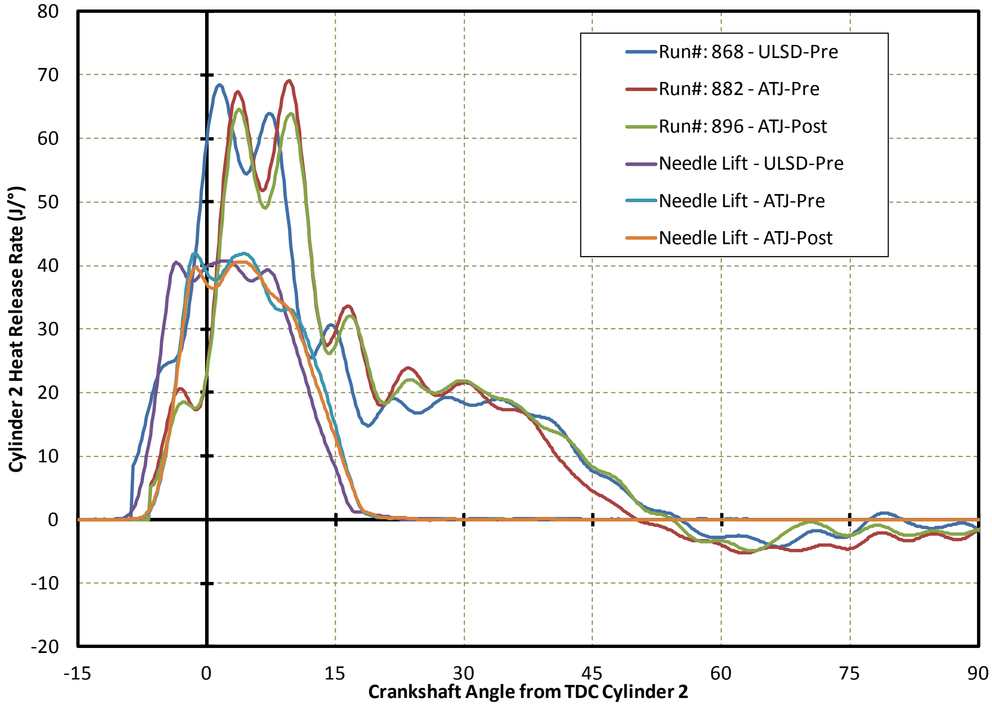

Figure A-26. Heat Release Rate Histories for 2600-RPM and 100% Load

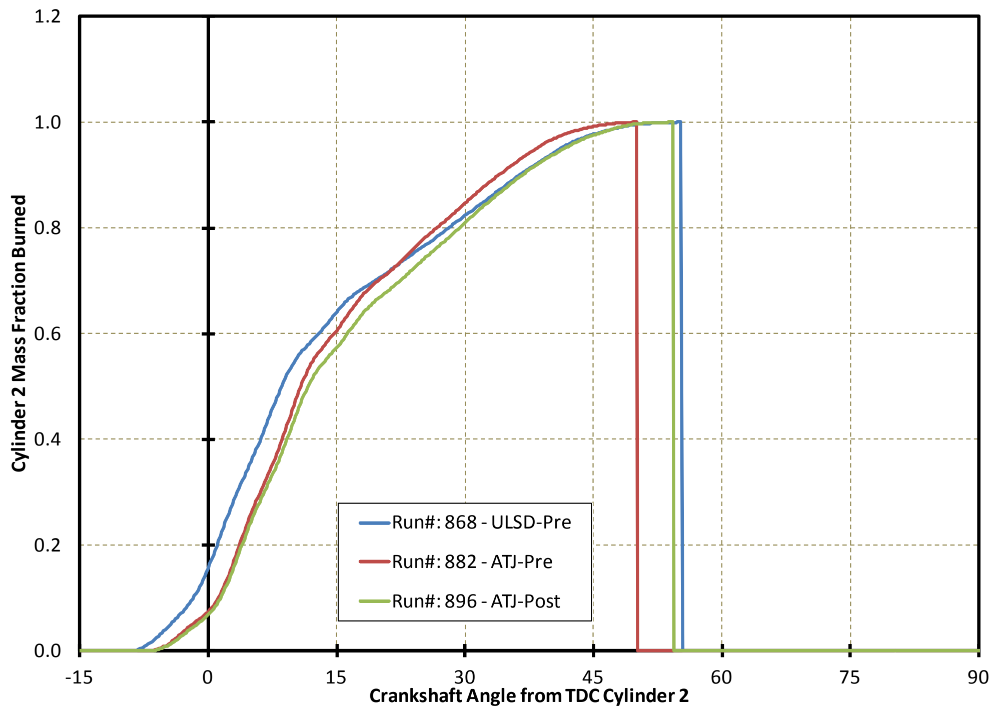

Figure A-27. Fuel Mass Fraction Burned for 2600-RPM and 100% Load

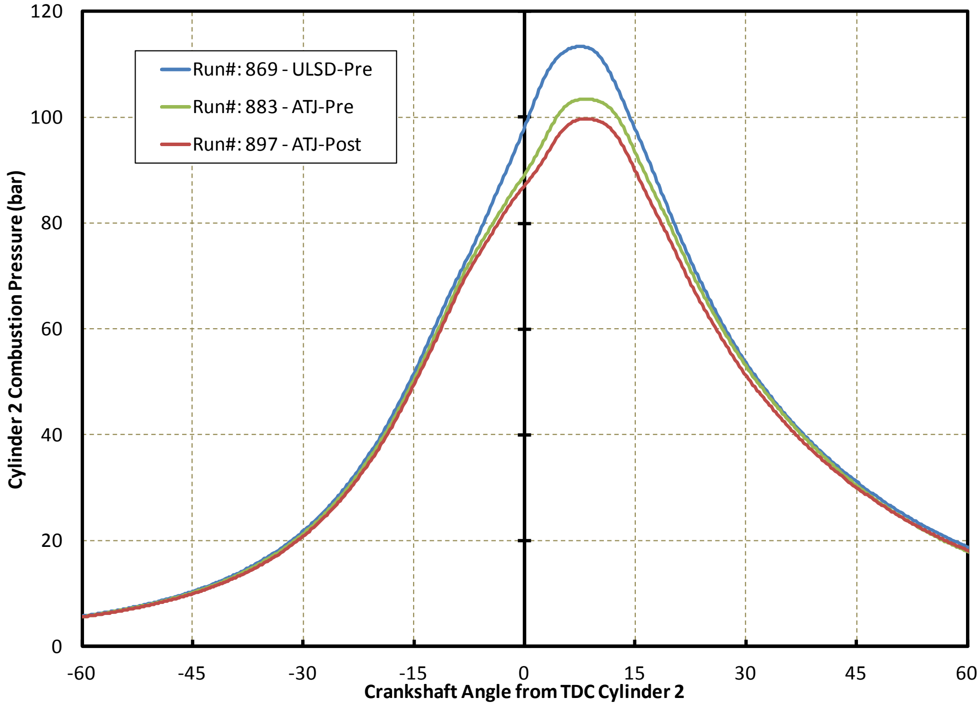

Figure A-28. Pre-Chamber Pressure Histories for 2800-RPM and 100% Load

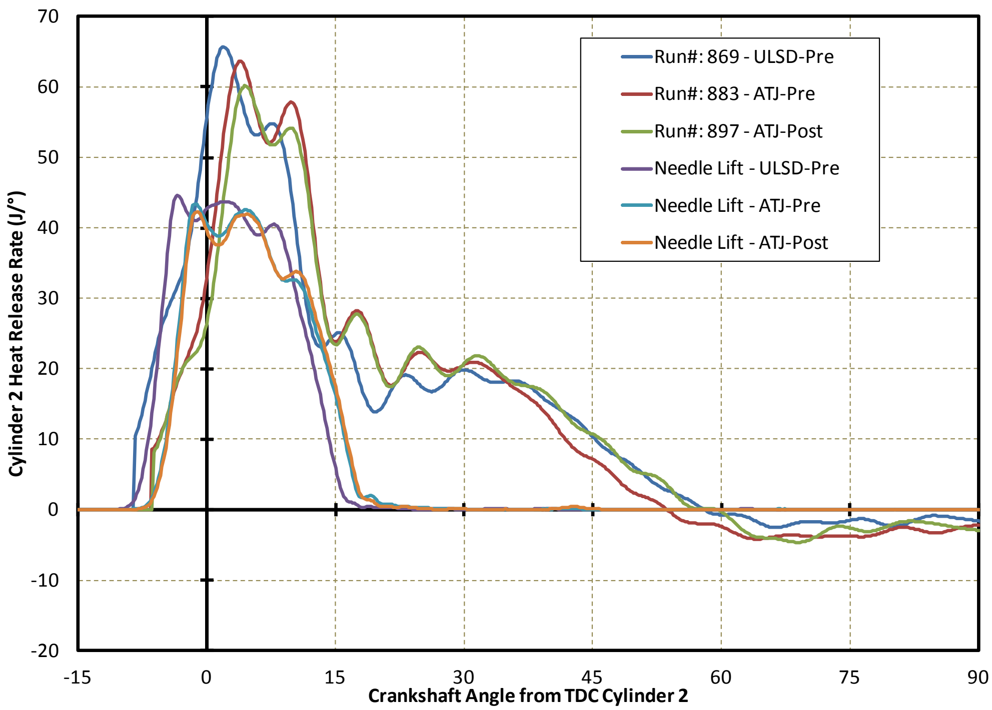

Figure A-29. Heat Release Rate Histories for 2800-RPM and 100% Load

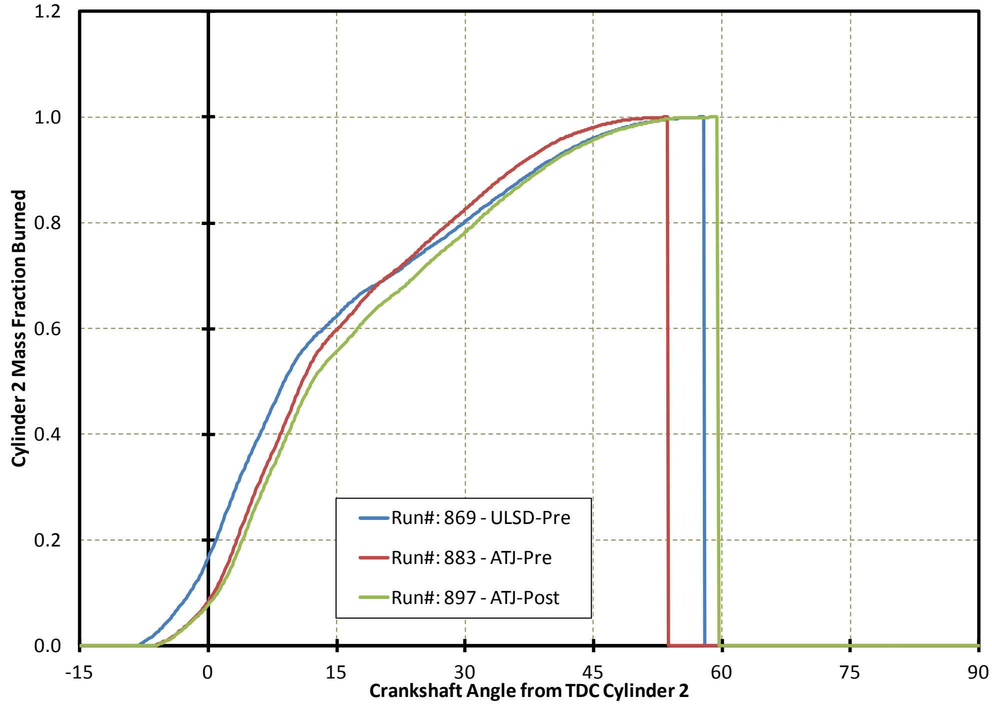

Figure A-30. Fuel Mass Fraction Burned for 2800-RPM and 100% Load

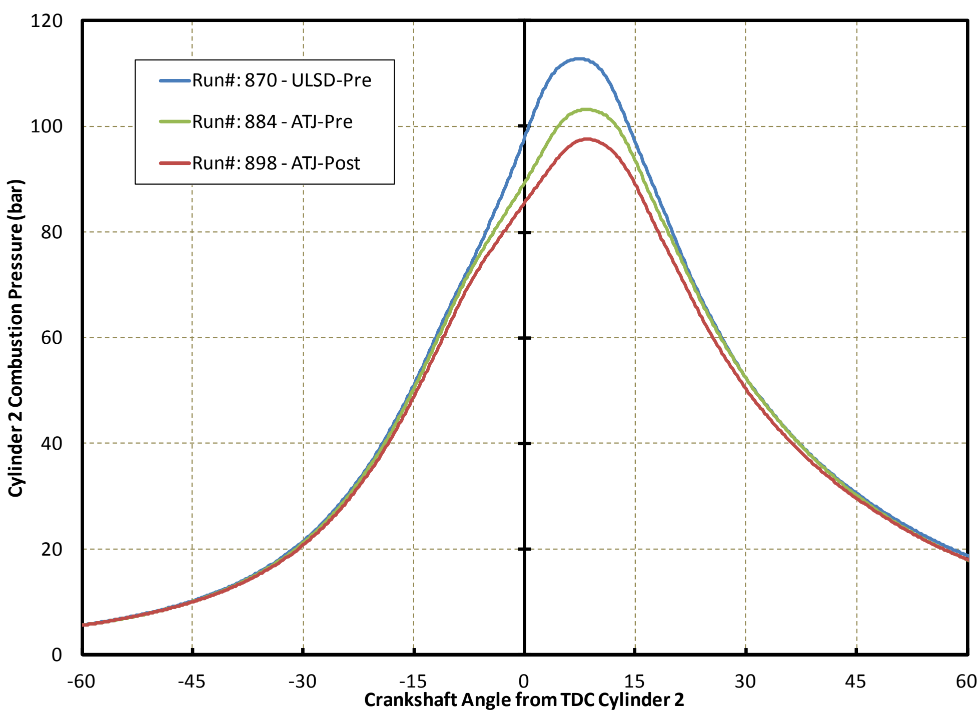

Figure A- 31. Pre-Chamber Pressure Histories for 3000-RPM and 100% Load

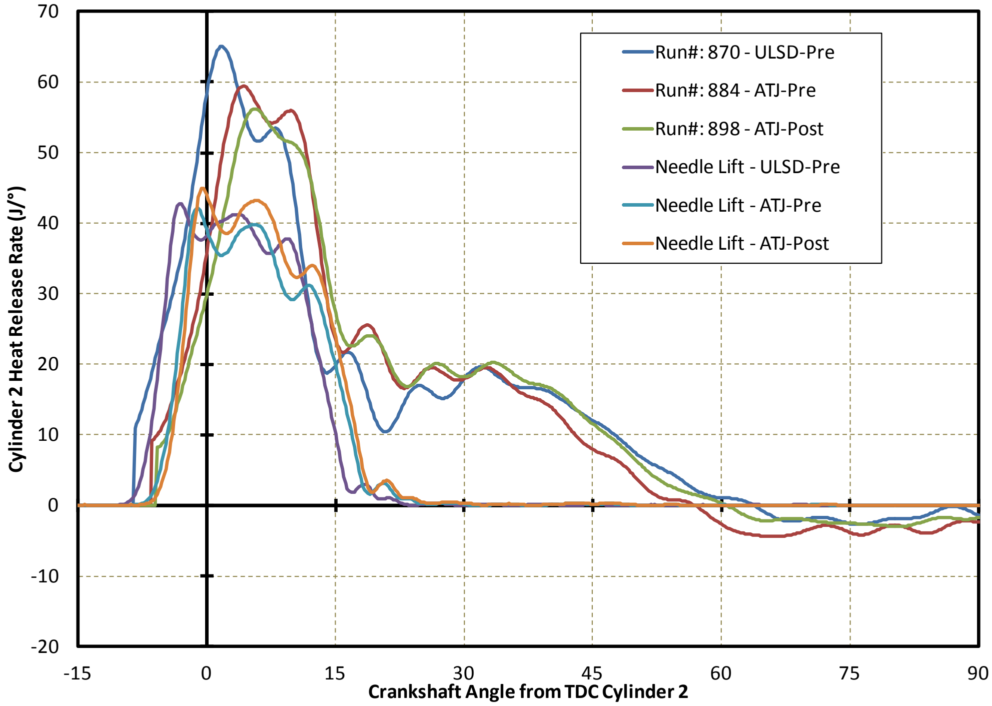

Figure A-32. Heat Release Rate Histories for 3000-RPM and 100% Load

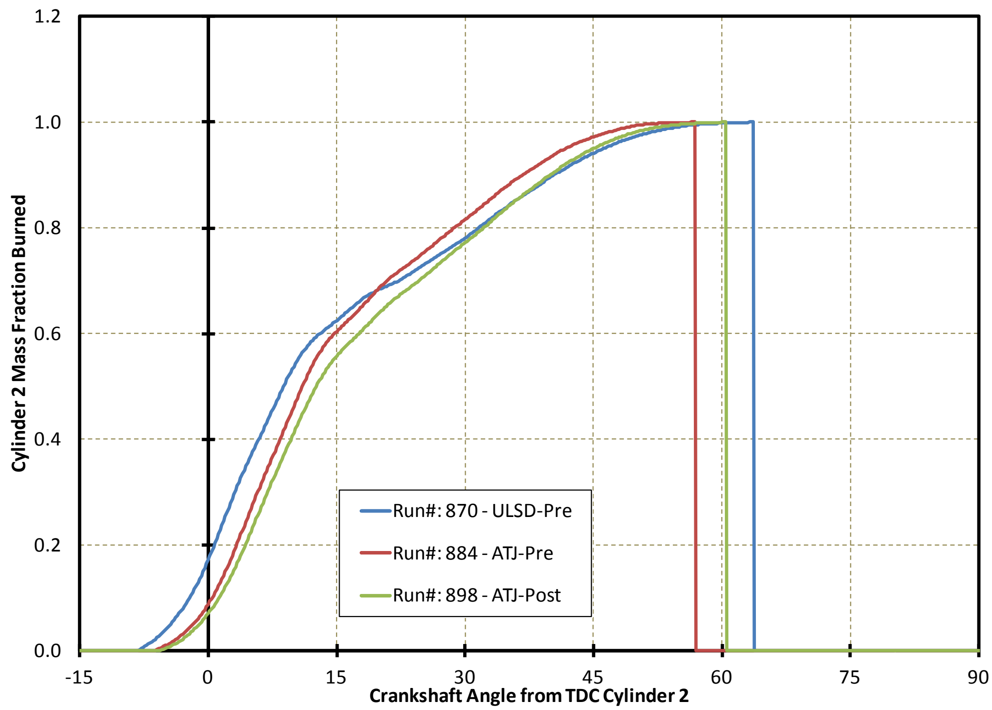

Figure A-33. Fuel Mass Fraction Burned for 3000-RPM and 100% Load

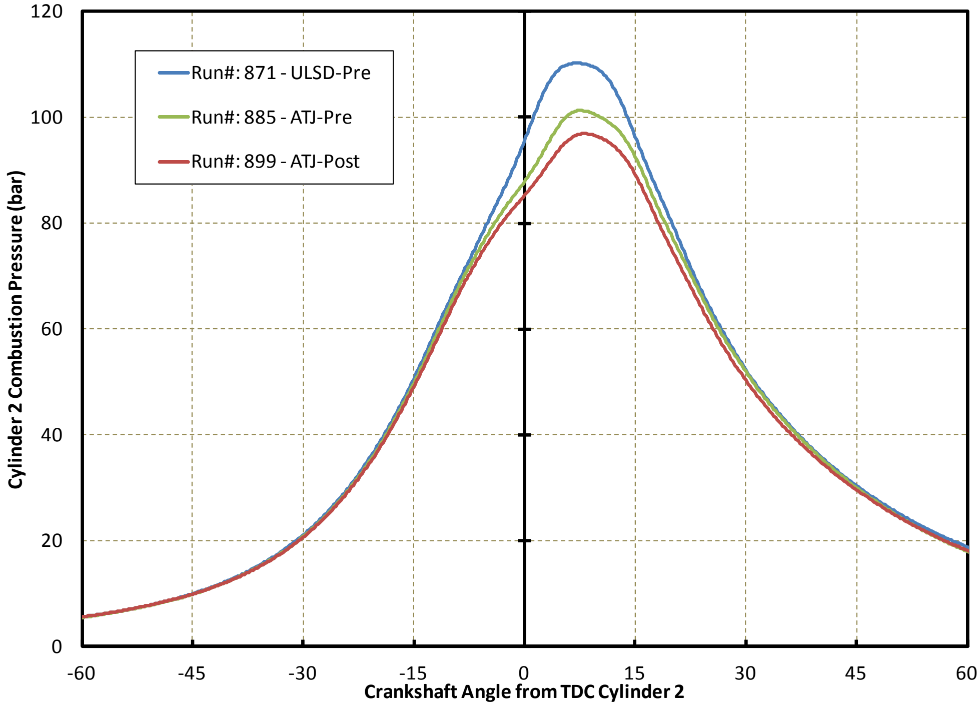

Figure A-34. Pre-Chamber Pressure Histories for 3200-RPM and 100% Load

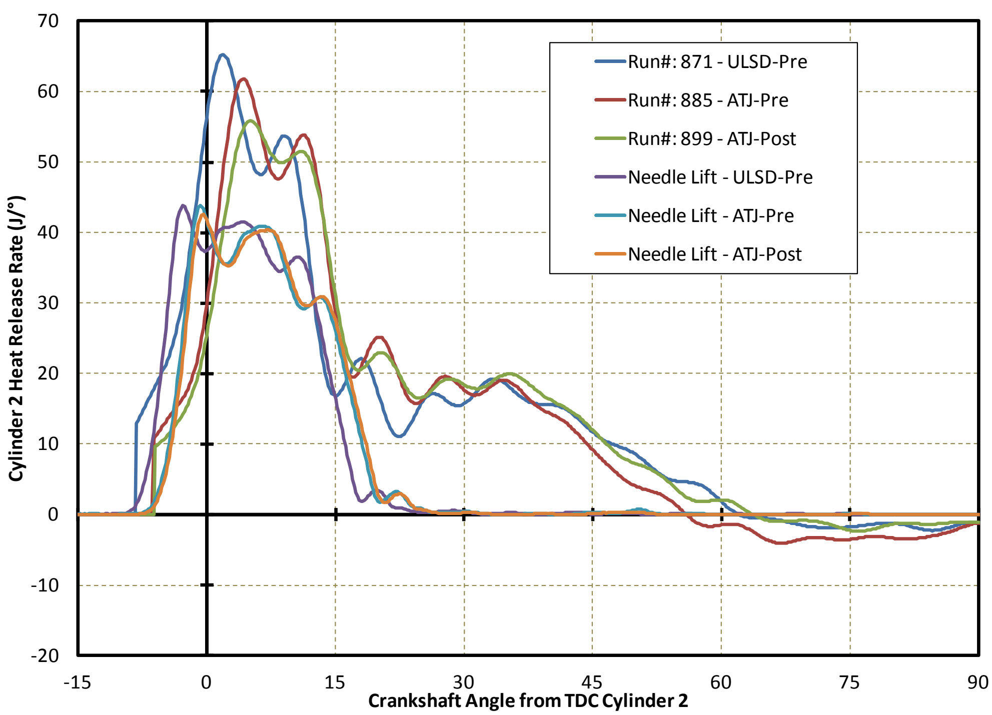

Figure A-35. Heat Release Rate Histories for 3200-RPM and 100% Load

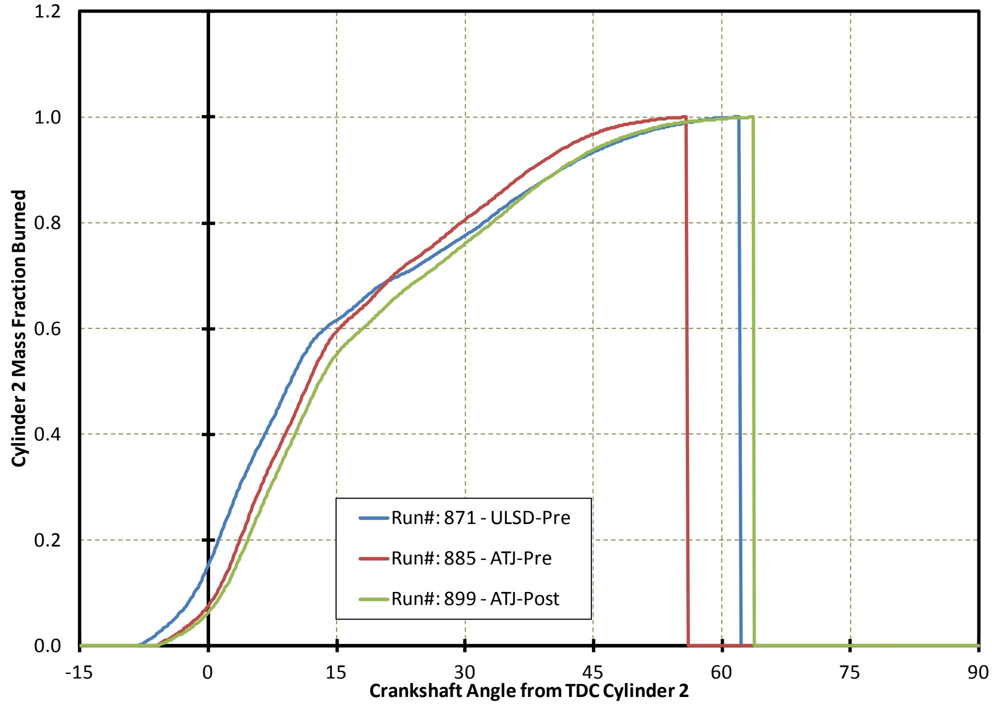

Figure A- 36. Fuel Mass Fraction Burned for 3200-RPM and 100% Load

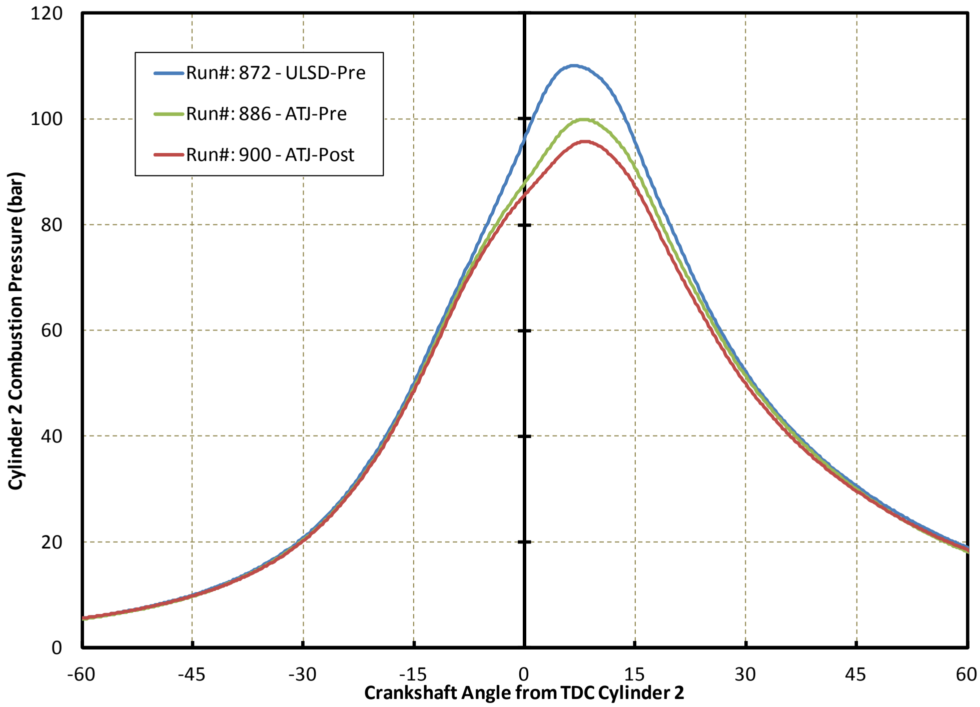

Figure A- 37. Pre-Chamber Pressure Histories for 3400-RPM and 100% Load

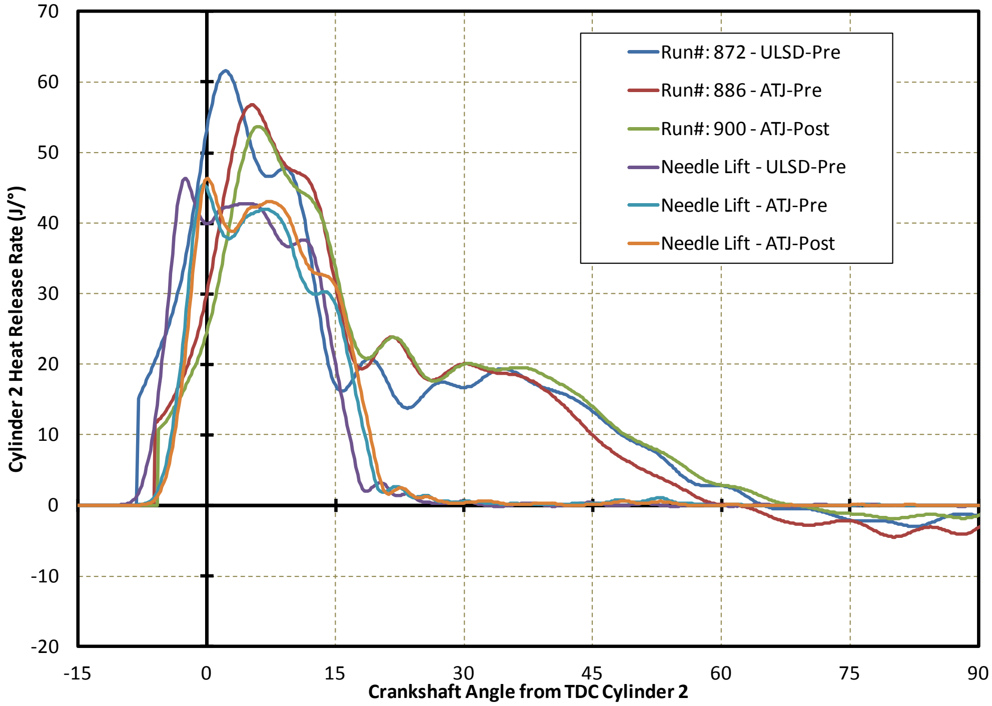

Figure A-38. Heat Release Rate Histories for 3400-RPM and 100% Load

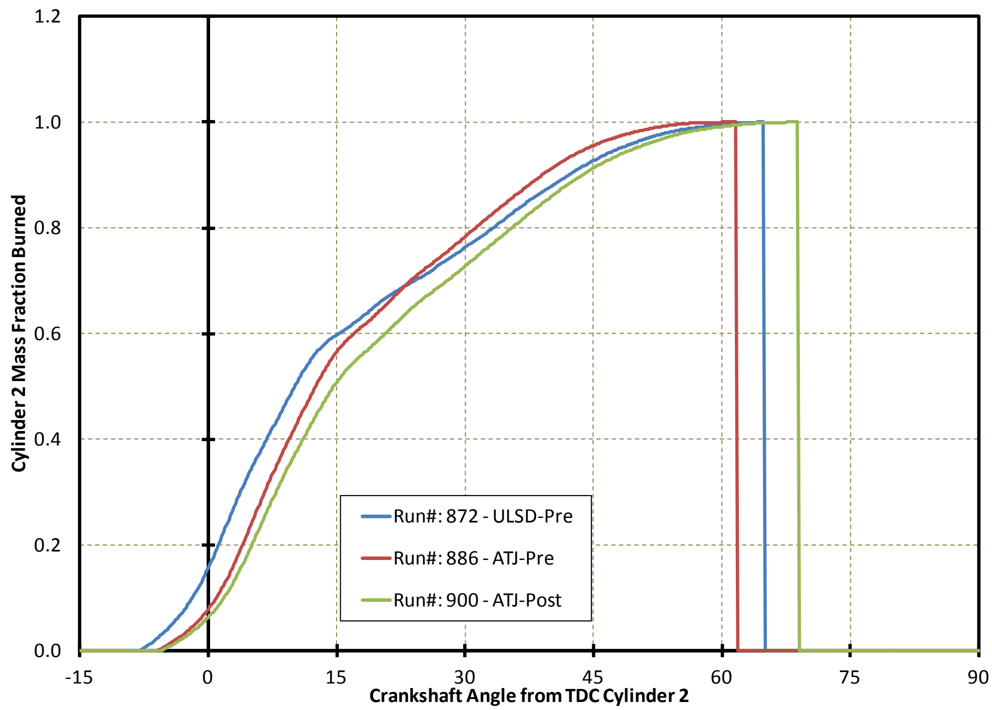

Figure A-39. Fuel Mass Fraction Burned for 3400-RPM and 100% Load

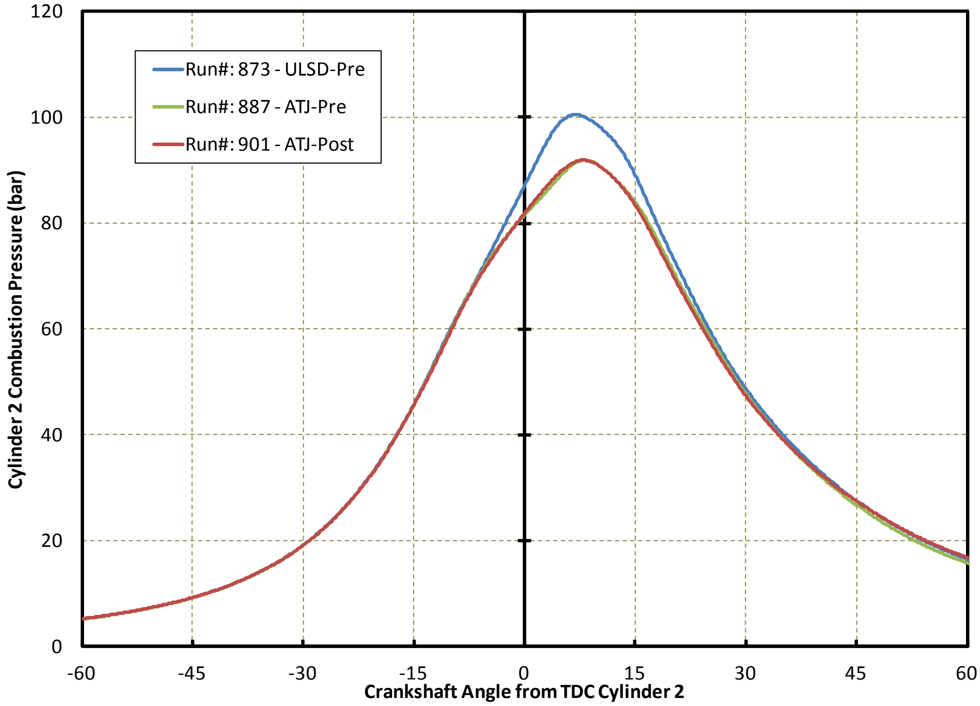

Figure A-40. Pre-Chamber Pressure Histories for 3600-RPM and 100% Load

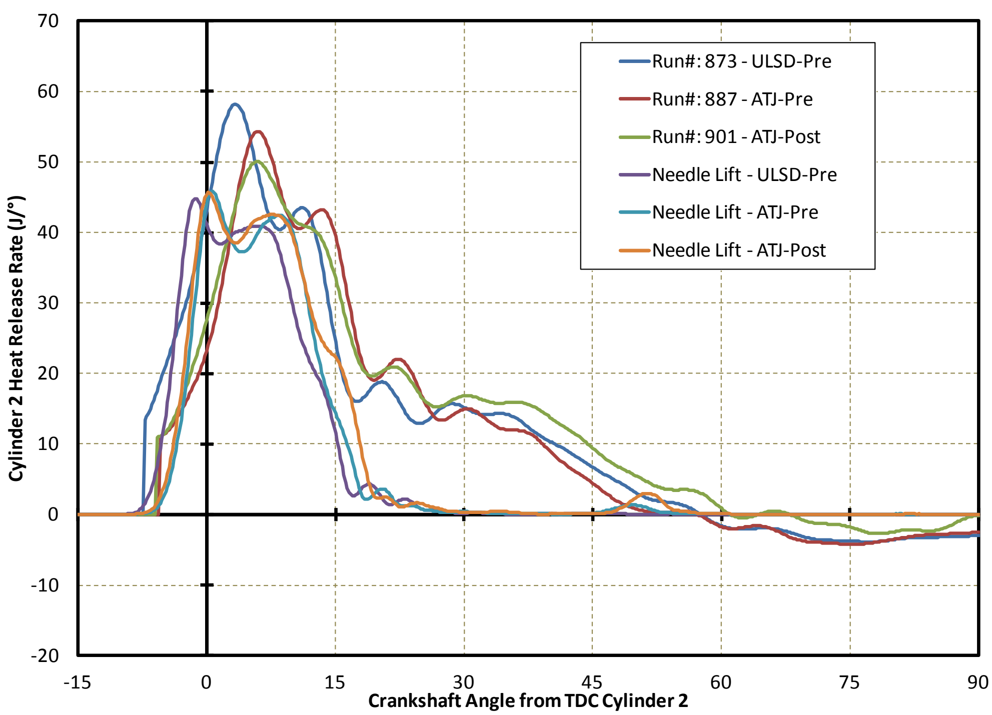

Figure A-41. Heat Release Rate Histories for 3600-RPM and 100% Load

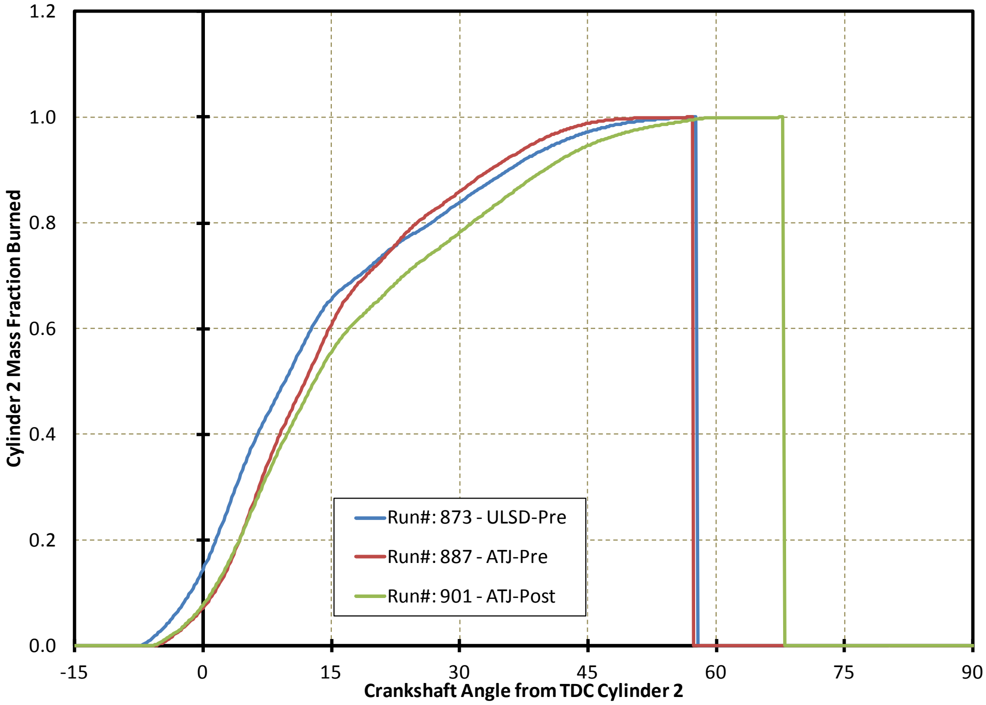

Figure A-42. Fuel Mass Fraction Burned for 3600-RPM and 100% Load